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[illegible] VARIATIONS IN AMBIENT
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[illegible] SKILL AND SENSORY SENSITIVITY*

*Subtask under Psychophysiological Studies, USAMRL Project No. 6-95-20-001, Subtask, Climatic Effects on Psychophysiological Abilities.

REPORT NO. 300

EFFECTS OF VARIATIONS IN AMBIENT TEMPERATURE ON CERTAIN MEASURES OF TRACKING SKILL AND SENSORY SENSITIVITY*

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Report No. 300
Project No. 6-95-20-001
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ABSTRACT

EFFECTS OF VARIATIONS IN AMBIENT TEMPERATURE ON CERTAIN MEASURES OF TRACKING SKILL AND SENSORY SENSITIVITY

OBJECT

The present study was designed to obtain information regarding the effects of ambient temperatures ranging from -10° to +40° C on 5 different measures of human performance: skill in using movement and pressure tracking controls, tactile and kinesthetic sensitivity, and strength of hand grip. The 2 types of tracking controls have wide military and industrial applications and the other 3 performances are basic to the operation of a great number of machine systems.

RESULTS

Kinesthetic sensitivity and pressure tracking were significantly impaired at the low end of the ambient temperature range, while tactile sensitivity, hand grip and movement tracking showed decrements at both ends, impairment being greater at the low than at the high. These relations between ambient temperature and performance were dependent upon the length of exposure to the experimental temperatures. The characteristics of recovery following exposure differed among the measures taken, tactile sensitivity, which was affected after relatively short exposures, recovering very rapidly.

CONCLUSIONS

Signs of impairment in human performance may appear when ambient temperature varies outside rather narrow limits. Characteristics of this impairment differ in different types of performance. Different sense modalities are differentially sensitive to temperature variations in terms of the durations of exposure necessary to produce signs of impairment and in terms of the characteristics of their recovery following exposure.

The results have provided information which can be of value in the design of machines and equipment to maximize the efficiency with which man-machine systems can function under adverse temperature conditions. They have indicated that some control and display systems may be used

more efficiently than others under extreme temperature conditions and have suggested ways in which different approaches to maintaining adequate levels to temperature, e.g., protective clothing, heating the work space, locally heating control surfaces, may be tested.

RECOMMENDATIONS

Results of this study suggest 2 main recommendations:

1. Information of the kind obtained during the research should be made available for the design of methods to minimize the adverse effects of environmental conditions on human performance.

2. Further systematic investigations should be conducted to add to this body of information. Such investigations should be designed to determine relations between environmental conditions and performance, including ranges over which efficient performance can be expected; to study the effects of duration of exposure on performance; and to observe the characteristics of recovery from exposure. The environmental variables investigated should include humidity, air velocity and radiation as well as ambient temperature, and particular attention should be given to the effects of interactions between these variables. The performance studied should be representative of the wide variety of skills required of military personnel and emphasis should be placed on perceptual as well as motor aspects of performance.

Submitted 25 February 1957 by:
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EFFECTS OF VARIATIONS IN AMBIENT TEMPERATURE ON CERTAIN MEASURES OF TRACKING SKILL AND SENSORY SENSITIVITY

I. INTRODUCTION

One prominent feature in the history of modern military operations is the increasing dependency of success upon the efficiency of man-machine systems. More and more it has come to be recognized that man's limitations may set the pace for the efficiency of such systems and that it is vital to know the nature of these limitations. It is now well known that man-machine combinations operate in environments containing a number of factors which may seriously affect man's performance and thus the efficiency of an entire system. The present research is concerned primarily with one of these factors, the temperature of the external environment.[1]

Information already available establishes the fact that the efficiency of performing a wide variety of skills may be affected adversely by even small changes in ambient temperature above or below the range to which man is accustomed. Such impairment of performance constitutes a particularly serious problem in planning and executing military operations under the extreme temperature conditions of the tropics on the one hand and the sub-arctic on the other. Even at temperatures well within these extremes the problem may still be a serious one. During the winter of 1950-51 the United States Forces in Korea had as many as 6,000 cold injury casualties (1). It can be expected that the efficiency of performing many skills was adversely affected long before the symptoms of injury appear.

It is certain that information regarding effects of variations in environmental temperatures on the performance of skills could be put to practical uses, as well as add to our knowledge of human behavior. Such information could be considered in the design of machines and equipment so as to maximize the efficiency with which they can be used under extreme atmospheric conditions. It could enter as a factor in the planning and execution of military operations, the success of which depend upon the efficiency of man's performance. It could be important in deciding on methods of training and of acclimatizing military personnel for duty in theatres of operation characterized by consistently extreme temperatures or by wide fluctuations in temperature.

[1]Referred to as "ambient" temperature.

It is apparent from research information already available that the external environment may exert its influences in a number of different ways. It may affect an individual's capacity to deal with the incoming sensory data upon which performance of a skill depends and it may interfere with the way in which he responds to these data. The present study was designed to obtain information regarding the effects of ambient temperatures ranging from -10° to + 40° C on five different measures of human performance. Two of these involved the measurement of tactile and kinesthetic sensitivity, sense modalities playing basic roles in many of the skills which military personnel are required to perform. The third was a measure related to good manual dexterity and accurate finger movements. The last two were measures of skill in using two types of machine controls, movement and pressure, both of which have wide military and industrial applications.

There were several major questions which the research set out to answer. What is the ambient temperature range over which efficient performance is maintained? Are different measures of behavior affected differently? What are the effects on performance of increasing durations of exposure to a particular ambient temperature? What are the characteristics of recovery from exposure to different ambient temperatures? How is skin temperature related to ambient temperature and to the various measures of performance? The results of the investigation have provided information which answers these questions, within, of course, the limits of the research design. In addition several other points have arisen. However, before discussing any details it will be well to examine the general background of the present study and to become familiar with the work of other investigators.

II. THE GENERAL BACKGROUND OF THE PRESENT RESEARCH

Interest in the effects of atmospheric temperature on man's performance has a long past (5), but systematic research into the nature of these effects has only a short history. This history began with industrial field research conducted early in the present century when relations between variations in temperature of the work environment and variations in performance on the job were studied. Distinct seasonal variations were reported in the output of workers engaged in a number of tasks requiring different kinds of skills (15, 54, 57). Hourly output was found to decrease as the weather grew warmer. Generally, summer output was lowest, then spring and autumn output, with winter highest. In other industries where atmospheric conditions varied from site to site during all times of the year wide differences in performance also were recorded. For example, in a group of collieries (55, 56), working capacity could be measured in terms of rest pauses taken from work and time to fill the standard tubs and trains. Temperatures in the hottest places varied only slightly more than 20° F from temperatures in the coolest places, yet output was calculated to be 41% less in the former than in the latter. In other words, working efficiency was only 59% as high in the hot environment as it was in the cold. In another field study (60), this time concerned with the efficiency of fine linen weaving, similar trends were found. It was possible to observe variations in performance as temperature changed with relative humidity practically constant. The results showed that productive efficiency improved as temperature increased up to 73° F, beyond which efficiency deteriorated. In this instance, even though the machine aspects of the process would have benefited from still higher temperatures, the effects of temperature on man's performance were the limiting conditions for the overall efficiency of the system. These and a number of similar studies called attention in a very striking way to the important effects which man's atmospheric environment may have upon the efficiency with which he performs a wide variety of industrial skills.

Much more recently, problems of this same general nature have been the subjects of field investigations carried out in military settings. Marked decreases in the sensitivities of certain sensory systems on exposure to cold have been demonstrated (32) and effects of cold acclimatization on sensitivity have been studied (31). Deterioration in several types of skill performance during exposure to hot environments has been noted (30, 3). Observers (36) have reported that "psychophysiological factors seemed to limit endurance...." of task forces operating in arctic conditions.

These field studies, both industrial and military, are very suggestive of answers to some of the questions in which we are at present interested. However, the field approach has serious disadvantages which research workers using it have recognized for a long time. The nature of the field situation frequently does not allow for the level of control necessary to sort out the relative contributions of a number of variables, any or all of which may be influencing performance. It is for this general reason that research workers are tending to seek their answers more frequently in the laboratory than in the field. Problems which were noticed first in man's working environment may be examined in the laboratory and possible solutions finally tested in the field. The background against which the present research must be viewed consists of information provided by both field and laboratory studies. When this information is examined, eight main problems are readily recognized.

A. Variations in Temperature Effects

As has been pointed out already, there is ample evidence to establish as a fact the observation that the performance of human skills may be affected significantly by variations in ambient temperature. This evidence also indicates that temperature effects on performance vary with different skills. The performance of some skills is extremely sensitive to variations in ambient temperature, but other skills may be only slightly affected, if at all, over fairly wide ranges of temperature.

The majority of research studies have been concerned with temperature effects on the performance of skills which emphasise some form of physical work ranging from manual dexterity to moving heavy loads. These studies (e.g., 2, 3, 6, 12, 14, 30, 34, 35, 45, 48, 53) are consistent in showing that variations in ambient temperature are associated with decrements in performance, but they also suggest that certain types of performance may be more sensitive to temperature effects than are others. For instance, in one study (19) exposure to cold did not alter reaction time to visual stimuli, but markedly diminished finger dexterity. The work of Gibbs (17), Hunter, Kerr, and Whillans (22), Mackworth (32), and other investigators is leading to a better understanding of these selective temperature effects in terms of the bodily mechanisms upon which different types of performance depend.

Similar variations in temperature effects have been observed in studies of performance emphasising perception and "mental work." For instance, a study (3) of the effects of heat stress on the performance of a task involving "anticipatory perception and judgment" reported that no important effect due to heat level could be observed. On the other hand, another study (30) demonstrated a significant deterioration in performance as measured by an increase of errors in a coding task when the effective temperature was raised to similar levels.

B. Temperature Effects on Components of a Skill

It is not always the entire performance of a task that deteriorates under adverse environmental conditions; particular components of a skill may be affected first. Recent research (9, 10) has illustrated what may happen in this regard. When exposed to heat, subjects, who were required to respond to a number of signals spread out in their visual fields, tended to miss signals particularly at points well away from the central task upon which they were concentrating their attention. The investigator has described this as "... a tendency for the field of awareness to be funnelled toward the centre...," a tendency which increased with the length of exposure to heat. Such differential effects of adverse environmental conditions are of considerable importance in military operations and deserve much more systematic study than they have so far received.

C. Temperature Range of Efficient Performance

One of the early field investigations (60) reported that productive efficiency increased with increasing temperature up to a certain point beyond which it decreased. Evidence of this kind presents us with the important problem of determining the optimal ranges in atmospheric conditions for efficient performance.

The results of early laboratory studies suggested that, even within very limited ranges of ambient temperature change, work done and time taken to perform different tasks varied as temperature varied. For example, in one study (39) subjects engaged in heavy lifting tasks did 15% less work at 75° F than at 68° F. In another study (48) involving skill in making continuous adjustments of a control mechanism, accuracy deteriorated significantly with variations of temperature 5° F above or below the temperature to which the subjects were acclimatized. Evidence of these kinds indicates that, for some types of performance at least, the optimal temperature range may be very narrow.

A number of studies have demonstrated how the limits of this optimal performance range may be determined. One of the first experiments (27), designed with the precision required to define such limits with confidence, was concerned with the effects of heat on the performance of wireless operators. Hot and moist atmospheres were shown to impair seriously the accuracy of wireless telegraphy reception. Impairment first appeared when trained and acclimatised subjects were exposed to a temperature of 87.5° F on the effective temperature scale. As was the case in this study, the experiments so far reported have, on the whole, been designed to yield information about one end of the optimal performance range only. To determine the extent of the range as a whole a research design such as that used in one of the Quartermaster Climatic Research Laboratory studies (52) has advantages. In this study the effects of temperatures ranging from 50° to 100° F on performance of a visual-motor coordination task were determined. Graphs of performance showed that the optimum temperature was approximately 70° F and that performance fell off in temperatures higher and lower than optimum, with cold resulting in more rapid deterioration of performance than heat.

If our knowledge regarding temperature ranges for optimum performance is to be made more complete and usable, attention must be given to research of this kind. The importance of determining the temperature ranges over which efficient performance can be expected is clearly indicated in a report of research carried on at the Armored Medical Research Laboratory (19). This report includes the following statement: "The last temperature (-20° F with zero wind velocity) was selected because it was considered to be the lowest temperature at which both the personnel and the vehicular equipment of the Armored Command would be able to function without the occurrence of serious breakdowns."

D. Relation of Level of Skill to Temperature Effects

There is evidence that the subject's level of skill at a task is related to the effects which variations in ambient temperature may have upon his performance. Some laboratory studies (27) have indicated that the accuracy of those subjects most proficient in their skills withstood the deleterious effects of high temperatures more easily than the accuracy of less skilled subjects. Other studies (30) have reported that, when the amount of work done is the criterion of efficiency and output is not restricted in some way, it is the performance of the best workers that deteriorates most. This evidence has been interpreted (30) as indicating that ambient temperature effects are most pronounced when an individual is performing at full capacity, either by working hard at a task calling for physical effort or by trying with limited success to perform a task requiring a high level of skill.

E. Relation of Incentive Levels to Temperature Effects

When exposed to environmental stresses man may still maintain his efficiency of performance, at least for a time, by putting more effort into his work. Recently studies (28, 46, 47) of the effects of incentives on performance under adverse temperature conditions have provided some interesting information in this regard. The results of the research showed that differences in temperature produced changes in accuracy of performance regardless of the level of incentive. However, all performance with high incentives was superior to performance with low incentives, even when the latter were operating under the most favorable temperature conditions. One investigator (46) has reported that the "... standard of performances with low incentives in this favorable climate could thus be maintained in the less favorable climates by an increase in the incentives."

F. Acclimatization

Considerable attention has been given to the study of physiological changes characteristic of acclimatization in hot and cold climates. Some of the research reported has implications for the relation acclimatization may have to temperature effects on performance. In one study (48), referred to earlier, the investigator reported that his subjects "... performed light skilled tasks most efficiently with a narrow temperature range similar to that of the seasonal and diurnal variations in temperature..." to which they had become acclimatized. Such observations as these suggest that the temperature range for optimum performance is not absolute but, rather, varies with the process of acclimatization.

The efficiency of skilled performance depends upon information received by way of the various sense organs. Research has shown that variations in ambient temperature may affect the sensitivity of sense organs, thus influencing performance. Some of the sense organs involved in the multitude of skills requiring manual dexterity and coordination are located in the skin of the hands. Field observations (61, 62) in cold environments have indicated that "... Acclimatized people seem to keep their skin warm." Pure-bred Eskimos have warmer finger temperature than white men during the initial stages of exposure to extreme cold (36). Differences between acclimatized and non-acclimatized subjects in tactile sensitivity have been demonstrated in the field (31). This evidence is strengthened by recent research (33) showing increases in tactile sensitivity accompanying acclimatization induced under controlled conditions in the laboratory.

The importance of maximum efficiency in performance for military success places a premium on knowledge regarding acclimatization. Information about methods of maximizing acclimatization and about time required to acclimatize could be useful in planning operations requiring the shifting of troops from one temperature zone to another.

G. Basis of Temperature Effects on Performance

The picture which has been painted in the preceding paragraphs would not be complete without an examination of the basis upon which ambient temperature exerts its effects on performance. This basis need not be a single one; logically it might involve peripheral sensory or motor changes, central perceptual changes, or some combination of these. Although the research literature provides evidence of recent interest in this type of psychophysiological problem, relatively little information is yet available.

The most extensive attack so far on this general area of problems has involved both field and laboratory studies (31, 33). It has demonstrated that tactile sensitivity, as measured by two-point discrimination, and vibratory sensitivity decrease as a result of exposure to low temperatures, the lower the temperature the greater the decrease. These results have been substantiated by other investigators. One attempt (35) has been made to determine whether or not kinesthetic sensitivity is similarly affected; the negative results obtained may well be attributed to the method used to measure sensitivity.

The possibility that changes at a peripheral response level with variations in temperature may contribute to decrements in performance has received some support. Laboratory tests have shown that muscle and joint temperatures fall on exposure to low ambient temperatures. It might be expected that such drops in temperature would impair the normal functioning of muscles and joints and be reflected in the performance of various skills. Strength of hand grip is known to decrease when the hand is cooled (19). It has also been shown that the maximum speed of flexing the index finger decreases significantly after exposure to cold (22). Experiments (22) with the viscosity of synovial fluids has led to the conclusion that "the characteristics of synovial fluids are sufficient to account for increased forces required to move a joint, for loss in speed of movement and decrement in maximum strength exerted on exposure to cold."

Descriptions of human behavior in the tropics and the sub-arctic frequently imply that impairment of performance is due to central motivational and perceptual states. Until very recently this possibility had stimulated no systematic research. In 1954 reports of experiments on the restriction of the visual field in hot and humid environments (9, 10) suggested that exposure to high thermal conditions can be associated with "... a tendency for the field of awareness to be funnelled toward the center." Although these experiments tell us very little about central states which may vary with ambient temperature and thus influence efficiency of performance, they do help to point to a general problem which warrants more attention.

H. Use of Protective Clothing

An obvious answer to what can be done to eliminate the adverse effects of low ambient temperatures is to use protective clothing. Like many apparently simple answers to complex questions this answer is not as satisfactory as it may at first seem to be. For instance, investigators at the Armored Medical Research Laboratory (19) reported that "the best glove combinations now available... are not capable of either keeping the hands warm or maintaining their functional efficiency." Research (6) also has shown that the efficiency of such performances as radar tracking, changing frequency and resuming voice transmission using standard radio equipment, and the manual operations in completing a call through a standard switchboard, all are lower with protective clothing than without. The protective clothing may interfere with the input of sensory information or with the responses required to perform a skill efficiently.

Research results now available suggest that the use of protective clothing may impair the performance of certain types of skills, but may not affect others (13, 16, 51). Different types of clothing, e.g., mittens and gloves, may give different amounts of impairment and these differences may show up at only extremely low temperatures (11). Particularly useful are research results which indicate the efficiency of practicing while clothed in protective equipment any skills that may eventually have to be carried out under adverse temperature conditions (18).

Examination of research of this kind suggests two general points worthy of re-emphasis. First, information regarding the nature of temperature effects on performance may be of considerable value in the designing and testing of protective clothing. Secondly, at least until further developments have been made, it is not safe to depend upon protective clothing as a completely adequate solution to the problem of maintaining efficient performance under adverse temperature conditions. For those particularly concerned, much practical information has been assembled in a handbook on "Physiology of Heat Regulation and the Science of Clothing" (38).

These are the problems with which the present research is concerned. With the general background in mind we can now proceed to examine its design and results.

III. RESEARCH DESIGN AND PROCEDURE

A. Research Design

The main features of the research design are shown in Table 1. It required twelve groups of subjects, six groups using movement controls for tracking and six, pressure controls - the "M" and "P" groups, respectively. For each of the M groups, which were exposed to different temperatures during Phase 4, the experimental series, there was a corresponding P group. With the exception of these two variables, ambient temperature and type of tracking control, all subjects in all groups received identical treatments throughout the experiment. This means that, except for tracking, there are in effect six groups, each of 12 subjects, for the assessment of performance under the six different temperature conditions.

TABLE 1

RESEARCH DESIGN

Group	1 General Instructions	2 Preliminary Training	3 Control Series	4 Experimental Series	5 Recovery Series
M1*				+40°	
M2	''	''	''	+10°	''
M3	''	''	''	+20°	''
M4	''	''	''	+10°	''
M5	''	''	''	0°	''
M6	''	''	''	-10°	''
P1*	''	''	''	+40°	''
P2	''	''	''	+30°	''
P3	''	''	''	+20°	''
P4	''	''	''	+10°	''
P5	''	''	''	0°	''
P6	''	''	''	-10°	''

*'M' groups used movement controls during tracking; 'P' groups used pressure controls.

The ambient temperatures of the experimental series for the six groups in each of the M and P series ranged from -10° to +40° C in steps of 10° C. This range was selected for two main reasons. First, the research was designed to provide several kinds of information, one being the temperature range for maximum performance of the behavior measured. This required that the range be wide enough to allow for impairment of performance at both the hot and cold ends, if, indeed, such variations in temperature were associated with impairment of the behavior studied. Second, it was considered important that the extreme temperatures should not be such as to cause symptoms of heat prostration, frostbite, shivering or pain, which would only have complicated later interpretation of the results. Previous research suggested that the range chosen should serve both these purposes.

Five dependent variables were measured: Kinesthetic and tactile sensitivity, hand grip, tracking skill, and skin temperature. During Phases 2, 3, 4, and 5 of the research design these various performances were always measured in the order shown in Table 2. One such series of measurements will be referred to as a "cycle." Preliminary training consisted of four cycles and the control, experimental and recovery series of one, four, and two cycles, respectively.

TABLE 2

ORDER IN WHICH PERFORMANCES MEASURED - ONE 'CYCLE

1	2	3	4	5	6	7
Skin Temperature	Kinesthetic Sensitivity	Tactile Sensitivity	Hand Grip	Skin Temperature	Tracking Skill: 'N' or 'P'	Skin Temperature

Although the research design was not a complicated one, success in carrying it out depended upon the satisfactory use of a number of techniques for control and measurement. The sections which follow are devoted to consideration of the essential features of these techniques.

B. Subjects

The 72 subjects participating in the main experiment were enlisted men in the United States Army. All but 8 had entered the service only shortly before serving as subjects. Table 3 gives information regarding their ages, heights, and weights. Ninety-four per cent of them were right-handed. Throughout the experiment the subjects performed all tasks using their preferred hands.

TABLE 3

DESCRIPTIVE DATA REGARDING SUBJECTS

	Mean	S.D.
Chronological Age	21.64	3.45
Height (in inches)	69.65	2.78
Weight (in lbs.)	159.30	24.14

Subjects were selected from groups of volunteers reporting daily to the laboratory. For technical reasons, which will be apparent later, only 2 subjects could be put through the procedure during any one day. The 72 subjects were divided equally among the 12 groups required by the research design. They were assigned to particular groups purely on the basis of what experimental conditions had been set up in the laboratory for the day on which they reported for work. This could not be considered a random assignment and, since the research design required equated groups if inter-group comparisons were to be made, it was essential to determine whether or not significant differences in pre-experimental levels of performance existed among the various groups. Table 4 summarizes the results of an analysis of variance carried out to clarify this important point, using measures recorded during the control series as indicative of pre-experimental levels of performance. It will be seen that no significant differences did appear and, therefore, inter-group comparisons are justified.

TABLE 4

ANALYSIS OF VARIANCE OF PERFORMANCE DURING CONTROL TRIALS

Performance	Obtained F	df n_1, n_2	5% Point for Distribution of F
Kinesthetic - Ave. Error	0.43	5.66	2.36
Kinesthetic - Const. Error	0.27	5.66	2.36
Tactile	1.97	5.66	2.36
Hand Grip	1.03	5.66	2.36
Tracking - Movement	1.02	5.30	2.53
Tracking - Pressure	0.84	5.30	2.53

C. Controlling and Varying Atmospheric Conditions

The research design required means of controlling and varying systematically the external environmental conditions in which performance was measured, as well as techniques for measuring performance.

Environmental conditions primarily affecting body temperature are: the temperature, humidity and speed of movement of the air, and radiation from surrounding surfaces in the environment. The present research was conducted in three laboratory rooms where these conditions could be controlled within small limits of variability. Table 5 summarizes measures of temperature and relative humidity taken systematically during each day's research. Measures of relative humidity were obtained in the customary way with a sling hygrometer, the dry and wet bulb temperatures being converted to relative humidity using tables provided by Bedford (4). Velocity of the air was zero during all research periods. The best that could be done in controlling radiation was to keep the surrounding surfaces in the environment constant throughout experimentation in each of the three rooms.

TABLE 5

AMBIENT TEMPERATURES AND RELATIVE HUMIDITIES

	Control Room				Experimental Room			
	Temperature °C		Rel. Humidity %		Temperature °C		Rel. Humidity %	
Group	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
M1 + P1	+24.38	0.83	55.28	7.48	+39.54	0.33	28.94	1.63
M2 + P2	+24.81	0.90	58.00	5.98	+29.54	0.20	32.80	1.90
M3 + P3	+23.48	1.28	57.38	6.97	+19.50	0.71	47.28	3.69
M4 + P4	+22.28	1.18	59.84	7.68	+10.00	-	-	-
M5 + P5	+22.72	1.20	54.89	5.10	0.00	-	-	-
M6 + P6	+22.57	1.15	55.85	5.13	-10.00	-	-	-

Two of the rooms were provided with temperature controls, one for the low and the other for high temperatures. Expert technicians were responsible for achieving and maintaining the temperatures required on particular days. Control of humidity, which is particularly important at high temperatures, was possible in the hot room within limits imposed by the temperature. The extent of humidity controls is shown in Table 5.

Research workers have frequently found it useful to express the warmth of the environment in terms of "effective temperature" (4). This measure takes into account the temperature, humidity and rate of movement of the air. Table 6 presents a comparison between the mean dry-bulb and effective temperatures in which the first three groups of the research design performed. It will be seen that effective temperature is consistently lower than dry bulb temperature. For the control room the differences are of approximately equal magnitudes and small in all instances. The differences are greater for the experimental room, but they decrease systematically as temperature decreases and disappear entirely at the lower experimental temperatures not included in the table. Dry bulb temperatures will be used throughout the present paper in reporting relations between ambient temperature and other variables. To use effective temperatures would only condense slightly ~~the high temperature end of these relations and would not alter their~~ general form.

TABLE 6

EFFECTIVE TEMPERATURE*

Groups	Dry Bulb Temperature - °C		Effective Temperature - °C	
	Control	Experimental	Control	Experimental
M1 + P1	24.38	39.58	21.11	28.44
M2 + P2	24.61	29.54	21.11	23.33
M3 + P3	23.46	18.50	20.56	16.67

*Determined on the basic scale as described by Bedford (4)

An inter-communication system connected the control and experimental rooms with another room in which measures of skin temperature were recorded. Through this system the experimenters dealing directly with the subjects reported the start and completion of each measurement of performance and any observations of the subjects' general behavior which might be of interest in the later interpretation of results. Such information was essential, particularly for the determination of the temporal distributions of measurements during the control, experimental and recovery series.

D. Measuring Performance

The following paragraphs describe the apparatus and techniques used in measuring the five main dependent variables.

1. Tactile sensitivity

Tactile sensitivity was measured using Mackworth's "V-Test" (31), shown in Figure 1. Results from the use of this apparatus have been shown to correlate highly with results obtained from other methods of measuring tactile sensitivity, including use of the classical two-point aesthesiometer (2). Mackworth's apparatus has advantages for studies of the present kind, particularly as it minimizes changes in skin temperature due to contacts with warmer or cooler surfaces during testing. The main feature of the apparatus were two sheets of plastic 232 mm long separated by a wooden wedge in such a way that the gap between them ranged from zero at one end to 13 mm at the other. Two rubber knobs were provided for moving the apparatus during test periods. Scribed on the sides of the plastic sheet were lines at intervals of 13 mm.

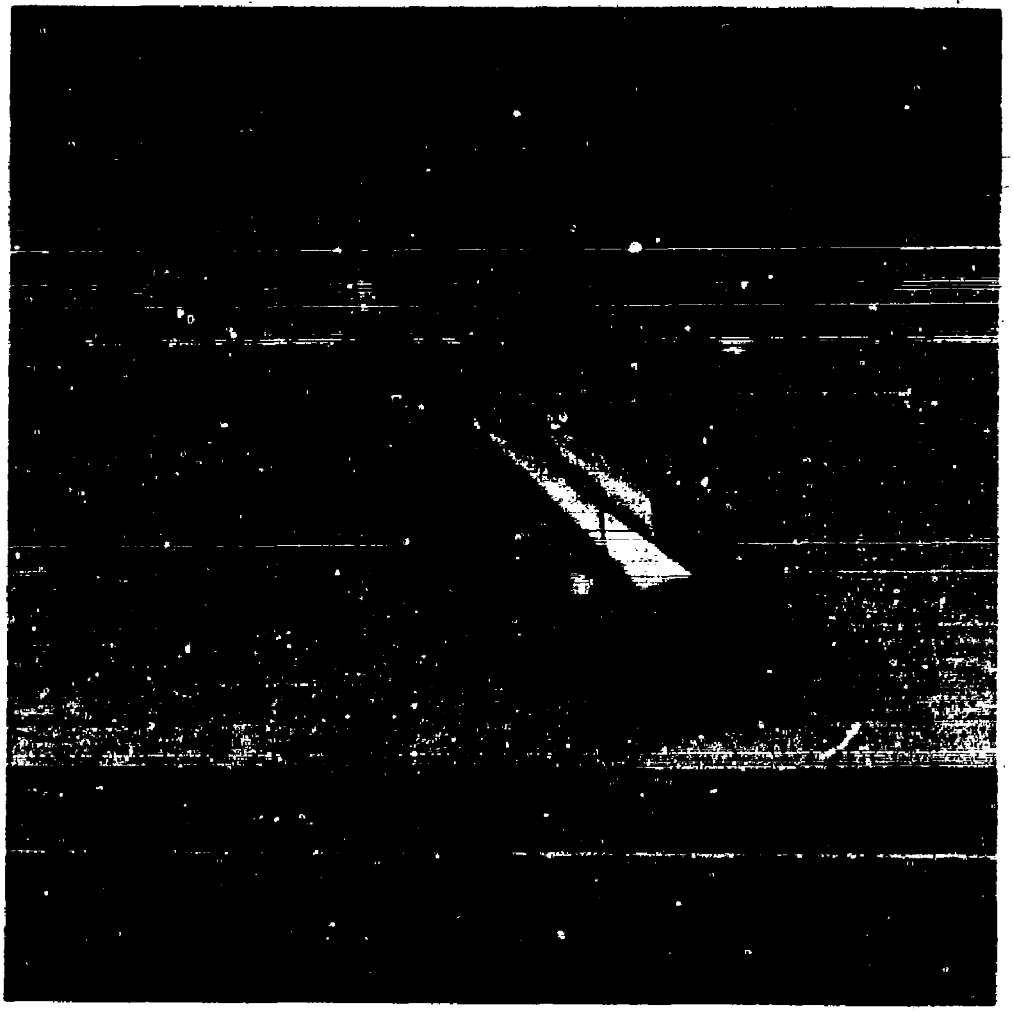

Fig. 1. Mackworth's "V-test" for measuring tactile sensitivity.

The subject was blindfolded during each test series. As shown in Figure 2 he was seated at a wooden table opposite the experimenter, the forearm of his preferred hand resting on the table top and the index finger of the hand extended. The experimenter moved the apparatus until one of the scribed marks was under the center of the finger tip. On instruction "now" the subject lowered his finger gently until it touched the top edge of the plastic sheets. He reported immediately whether or not he could detect the presence of a gap by saying "yes" or "no." Threshold determinations were made during each cycle of measurements using the psychophysical method of limits. Three descending and 3 ascending series were used, the gap size being varied by moving the apparatus under the subject's finger as required. Frequent "catch tests" were inserted to guard against any extraneous cues which might have influenced a subject's reports. The measure of sensitivity for any one cycle was taken as the mean of the 6 threshold determinations.

Fig. 2. Measuring tactile sensitivity.

2. Kinesthetic Sensitivity

The apparatus used in measuring kinesthetic sensitivity was developed at the University of Rochester (50) and is shown in Figure 3. It consisted of a horizontal metal shaft supported in metal bearings embedded in 2 walls of a black wooden box. Fastened to the subject's end of the shaft was a black plastic knob and at the experimenter's end, a plastic pointer along the center of which a thin line was etched. As the knob was turned this pointer moved over the surface of a 180° protractor scale, thus providing a means of measuring the angular extent of the movement. Internal mechanical stops were fitted to limit this to the 160°, 80° to either side of the vertical position. A felt brake provided just enough friction to maintain the setting when rotation of the knob had ceased. The rotating system moved easily with little inertia and was free from "rough spots" which might have provided local cues.

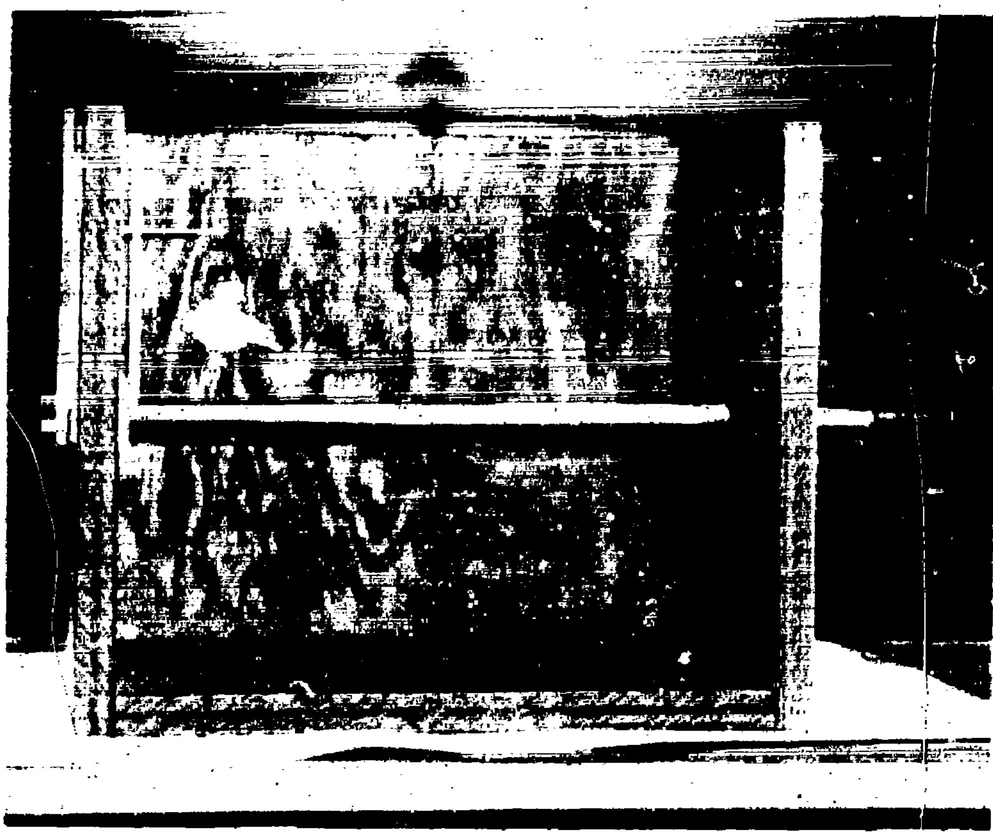

Fig. 3. Rochester apparatus for measuring kinesthetic sensitivity.

The subject was seated, blindfolded at the wooden table, the forearm of his preferred hand resting on an arm rest as shown in Figure 4. The experimenter set the pointer on his side of the shaft at 70° of the vertical position to the subject's right. The subject then grasped the knob lightly with the fingers of his preferred hand and rotated it in the following way: first, to the right until the stop was reached, then through 160° to the left stop, thirdly, by a return rotation 160° to the right, and finally to a setting which bisected this large angle. The first slight turn was to get the subject to a definite starting point; the second and third turns were to allow him to sample the angle, to get the "feel" of it; and the fourth turn indicated the accuracy with which he could make judgments based on the cues provided by the preceding rotations. Ten such judgments were obtained during each cycle of measurements, the angular distance between the subject's setting and the vertical position serving as the measure of accuracy.

Fig. 4. Measuring Kinesthetic sensitivity.

3. Hand Grip

Strength of the hand grip was measured in the conventional manner using a dynamometer calibrated in kilograms. The blindfold was removed and the subject remained seated. The dynamometer was held in the preferred hand, the arm hanging naturally at full length by the subject's side. On the instruction "now" the subject squeezed the dynamometer as hard as he could without changing his position. The experimenter then recorded the results of the trial and had re-set the pointer on the dynamometer scale. Two such trials were given during each cycle of measurements.

4. Tracking Skill

The apparatus used for measuring skill in both free-movement and pressure tracking is shown in Figure 5.[2] In this picture the wooden cabinet has been removed to show the essential mechanisms. Because of difficulties experienced by other research workers using electronic systems under conditions of widely varying ambient temperatures the present apparatus was based upon mechanical principles. Movement of the tracking stylus on the moving-paper polygraph was controlled by a control column terminated by a spherical brass knob. The relation between the displacement of the control and the amount of excursion of the stylus could be varied by changing the pivoting point of the arm supporting the stylus. For movement tracking the pivot was close, 5.0 inches, to the stylus, thus requiring a movement of one inch for maximum excursion of the stylus from its central position. For pressure tracking the pivot was moved to a position 9.3 inches from the stylus and a standard friction applied to the control column. Under these conditions a full excursion of the stylus from its control position required a displacement of the control column of only 0.20 inch and the rate of moving the stylus depended upon the amount of pressure exerted against the column.

The track to be followed was traced on the moving paper by a stylus operated by a cam from a small electric motor. Whenever the motor was running the target stylus moved repeatedly through a

[2] This apparatus was constructed in the workshop of the Department of Psychology, University College, London. It was based upon the suggestions from Dr. N. H. Mackworth and Mr. C. B. Gibbs of the M. R. C. Applied Psychology Unit, Cambridge, England.

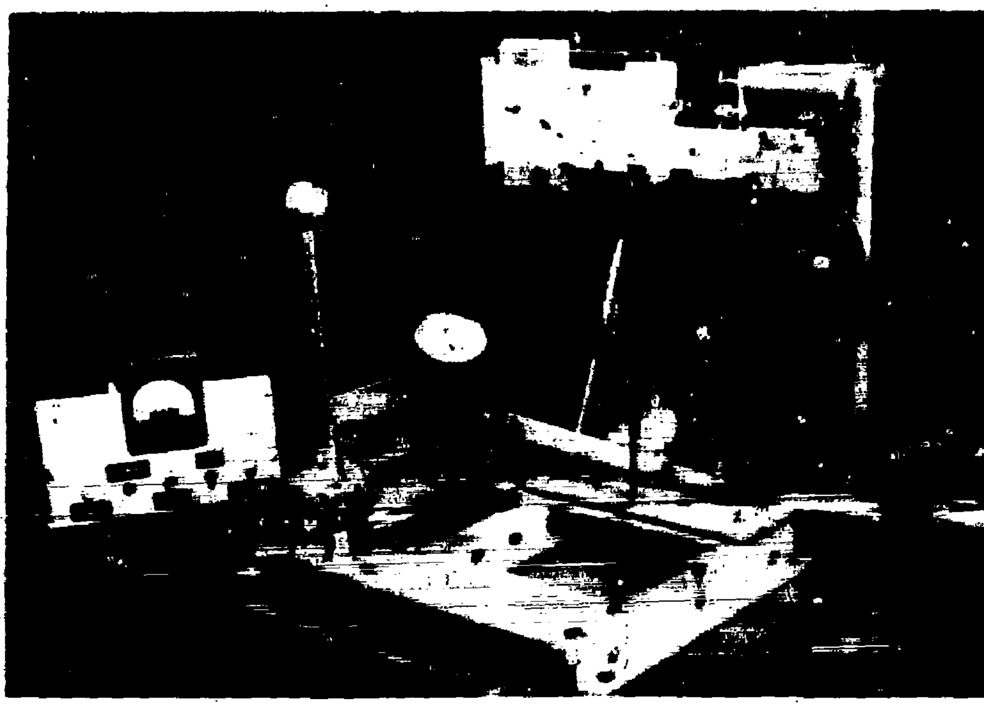

Fig. 5. Apparatus for recording tracking skill.

series of identical cycles, each of the cycles being 13.70 ± 0.85 seconds in duration. Both the tracking and target styli were fitted with soft colored leads pressed against the paper by adjustable springs. The track was in red and the subject's performance in blue, thus providing immediate knowledge of results and facilitating later analysis of errors. The experimenter's controls for various components of the apparatus were mounted in a single control box. Time was indicated by an electric clock wired into the control box.

A standard procedure was worked out for checking and calibrating the apparatus before each phase of each days' research began. Careful checking of the operation of each component part of the apparatus proved very valuable in that no serious breakdowns occurred during the entire experiment even though the apparatus received heavy usage under widely varying conditions. Two main features characterized the calibration procedure. It was essential for the later interpretation of results that the tracking problem remained the same under all experimental conditions. This meant that the duration and peak amplitude of each cycle of the track which the subject was required to follow had to be constant. Measurements of duration and peak amplitude were taken before each trial and adjustments made in the apparatus whenever necessary. Product-moment correlations between the durations of off and even cycles for a random sample of tracking trials gave a mean correlation of +0.97, which indicates how successful this calibration procedure was. Peak amplitudes did not vary throughout the experiment. The second feature of the calibration procedure involved adjustments to the friction on the control column before each period of pressure tracking to ensure that the amount of pressure required to displace the tracking stylus was maintained at approximately one pound.

After the apparatus was checked and calibrated the subject was seated on a stool in front of the control column as shown in Figure 6.

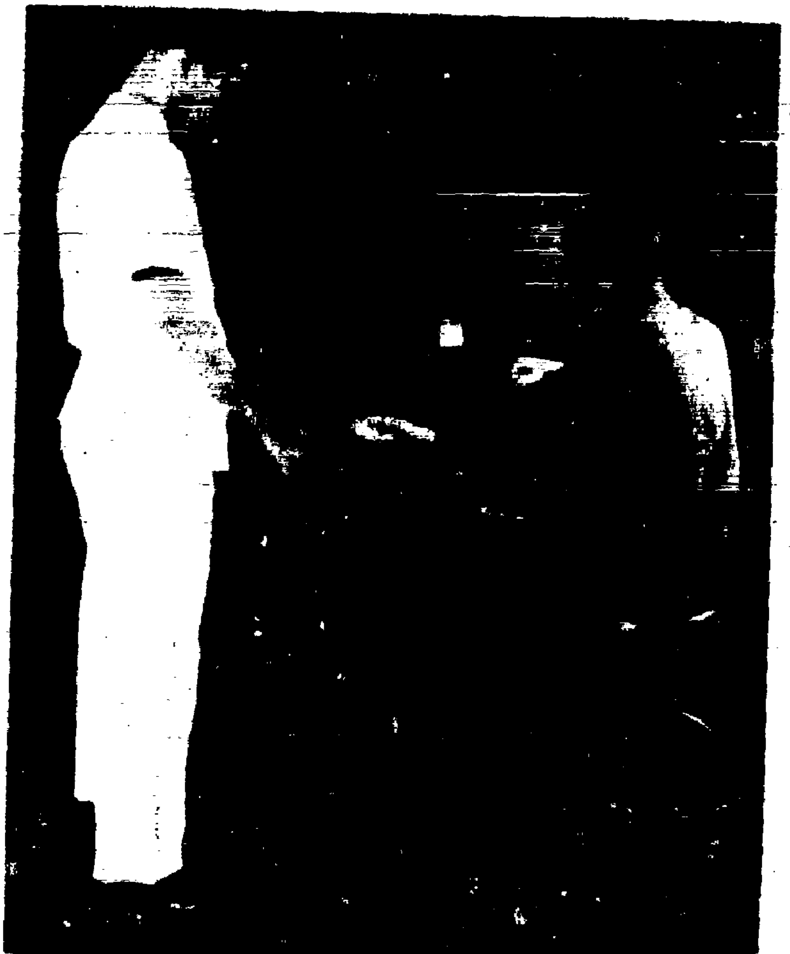

Fig. 6. Recording tracking skill.

This stool was adjustable so that the subject's forearm was approximately horizontal when operating the control. The brass knob at the top of the column was grasped by the fingers of the preferred hand. The preferred hand was always used, although there is evidence (49) that accuracy in tracking with the non-preferred hand is not significantly different from accuracy with the preferred hand in right and left-handed groups. Two knobs were available, one for use in the control room and the other in the experimental room. The latter was kept in the experimental room at all times. During preliminary training tracking periods were 10 minutes in length and during the other phases of the experiment, 5 minutes.

It was necessary to select one of several possible scoring techniques for analysing the tracking records and they were obtained. The decision was based upon analyses of data obtained during a preliminary experiment completed before the main experiment began. Previous experience had indicated that the final results of applying several different techniques correlated highly. There are, of course, advantages in using the simplest technique which produces reliable results and provides the desired information. For purposes of the present study it was decided to use a cumulative score of the errors in tracking, the subject's distance off the target in millimeters, measured at regular intervals of one second. Application of this measure to data from the preliminary experiment suggested that it might be possible to simplify the technique still further by measuring the records of performance during part rather than all of a tracking trial. This required an answer to the question: How closely do various part scores correlate with whole scores? The tracking records for all subjects in the preliminary experiment were scored in successive groups of 5 target cycles each and rank order correlations between scores for each of these groups and scores for the whole trial determined. The correlation between scores for the first 10 target cycles and scores for the whole trial was found to be 0.84; scoring fewer target cycles seriously reduced the correlation and scoring more increased it very slowly. Therefore, it was decided to define tracking error score as the sum of the distances off target measured at regular intervals of one second during the first 10 target cycles of a trial.

5. Skin Temperature

The method of measuring skin temperature was decided upon after preliminary trials in which a number of locations for the thermocouples were tried. Copper-constantan thermocouples were used. They were led into the various channels of a 16-position Brown Potentiometer.[3] Skin temperature data were needed primarily for the finger tips of the preferred hand, the hand used in all the measures of performance taken, but similar data were also recorded for 2 control locations. One of these was the finger tips of the non-preferred hand, which was exposed to the experimental atmospheric conditions but not involved in the movements and contacts with surfaces as were the fingers of the preferred hand. The other control location, a thermocouple on the dorsal or posterior and one on the ventral or anterior surface of the forearm, provided information as to the effects of the atmospheric conditions on the skin temperature of a part of the limb covered by protective clothing.

Leads from these thermocouples entered the input of the Brown Potentiometer, which was located in a separate laboratory room. The potentiometer cycled automatically through the various inputs and recorded the temperature of each on a moving-paper polygraph. The temperature could be read from these records with the aid of a properly calibrated template. One input position was reserved for the lead from a thermocouple immersed in a vacuum flask containing slowly melting ice, thus providing a calibration point for each record.

The thermocouples to the forearm positions were mounted in plastic mesh screens and were held in position approximately half way between the hand and the elbow by broad elastic bands secured at 2 points with adhesive tape. Since the finger tips of the preferred hand were used in all the various performances measured, thermocouples could not be fastened to them for the duration of the research session. Instead the leads from each thermocouple were pinned to the subject's sleeves, one to each sleeve. This left the thermocouple free to be grasped between the thumb and forefinger when skin temperature measurements were needed. The position of the subject during these measurements is shown in Figure 7. The potentiometer was allowed to cycle through its various positions for as long as was necessary to obtain stable recordings of finger tip temperatures. This usually required from 2 to 3 minutes.

Operation of the potentiometer was a full-time responsibility for one experimenter. He kept contact through the intercommunication system with each of the two experimenters who were measuring

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[3]Brown "Electronik" Potentiometer, Minneapolis-Honeywell Reg. Co., Brown Instruments Division, Philadelphia, Pa.

Fig. 7. Recording skin temperatures.

the various performances. This enabled him to mark on the potentiometer tape when each test began and ended for each subject. This information was necessary in order to relate each measure of performance with the skin temperatures at the time it was recorded.

Because skin temperature is affected by muscular activity and by contacts with objects in the environment, the subjects were instructed to use their hands only in carrying out the various tasks assigned to them. At other times they sat or stood with their hands immobile and away from any object in the environment, including their own clothing.

Although the reading of the polygraph records was a relatively simple task, it seemed advisable to check on the accuracy with which it was in fact carried out. Two of the investigators involved in the research read independently all the temperature recordings for the 12 subjects in the groups exposed to +40° C. There were 1008 individual readings for each investigator and there was an overall agreement in

92% of these readings. In only one case, where the difference was 0.50°, did the investigators disagree by more than an amount which involved estimations within the calibration of the template used in the readings, i.e., 0.25°.

E. Procedure

The procedure can best be described by reference to the various phases of the research design as set down in Table 1. Only two subjects were put through the procedure on any one day. Research began at about 8:30 a.m., and continued until approximately 3:30 p.m., with a mid-day interval of about an hour and a half. All equipment and apparatus was checked and calibrated before the day's research began. The subjects were first taken to the control room in the laboratory, where the preliminary training, and the control and recovery series were to be carried out. Here they were given general instructions regarding the background of the research and what would be expected of them. Since their schedule was to be a long one and since the level of their motivation was an important factor, every effort was made to gain good rapport and to clarify the general procedure. There were a number of factors favoring an interested participation in the research. The day's work was a break in the subjects' routines; it relieved them of other, more arduous duties; and it kept them in the laboratory where, except for the experimental phase of the study, temperature conditions were much more favorable than those outside the laboratory. The subjects' performance of the various tasks, the questions they asked and their spontaneous requests to participate as subjects in further research indicated that this initial period of contact with them was well worth the time and care put into it.

1. General Instructions

After rapport had been established general instructions were given regarding the nature of the day's schedule. This included descriptions of the steps involved in the procedure and instructions regarding special arrangements, such as transportation and messing. It also included specific instructions regarding the tasks which the subjects would be called on to perform.

2. Preliminary Training

Preliminary training then began. With the exception of skin temperature measurements the procedure followed was exactly the same as that employed during the control, experimental and recovery series. The 2 subjects were separated by screens. One began work on the sensitivity measurements, while the other received detailed instructions regarding the tracking task but did not actually practice it. When the first subject completed the kinesthetic, tactile and hand grip tasks he was moved to the tracking task and the second subject began the cycle. This alternation of subjects continued until each had completed the cycle 4 times. The importance of this preliminary training as a means of controlling practice effects on later performance is discussed in one of the following sections of this report.

The basic dress for all subjects was the fatigue issue clothing. In order to control any effects which the parkas, to be worn by groups 4, 5, and 6 during the experimental series, might have in restricting arm movements, these groups wore parkas throughout the entire research session.

After preliminary training the subjects were given an opportunity to ask questions regarding any aspect of the procedure. The schedule for the afternoon was discussed and they were then sent to mess.

3. Control Series

The subjects were allowed to rest for a short time after mess. During this period all equipment and apparatus were re-checked and re-calibrated. The schedule for the afternoon was then reviewed with the subjects; thermocouples were attached; and the subjects dressed in accordance with requirements of the experimental group to which they belonged. Subjects in the +20°, +30°, and +40° C groups wore cotton underwear under fatigue clothing, with cotton socks and Army issue shoes on their feet. Those in the 3 low temperature groups were dressed in arctic clothing consisting of the following: woolen underwear, woolen shirt, woolen padded trousers, and parka. Their feet were protected by woolen socks, felt liners and mukluk boots. With the hood over the head, the only exposed parts of the body were the face and the hands. The fact that no subject reported shivering or feeling cold except in the hands indicated that this way of dressing adequately served its protective function. After this preparation the subjects were put through one cycle of measurements as shown in Table 7. The mean time for completing this series was 15 minutes.

Each piece of apparatus was moved to the cold- or hot-room as soon as the second subject had completed his trials on it. Thus experimenters were prepared to begin the experimental series

TABLE 7

DURATIONS OF CYCLES OF PERFORMANCE DURING CONTROL, EXPERIMENTAL AND RECOVERY PHASES - COMBINED GROUP M AND P

Phase	Cycle*	Mean** Duration	Cumulative** Duration	Time at** Phase Temperature
Control	S - 1	7	7	
	T - 1	8	15	15
Move to experimental room		10		
Experimental	S - 1	8	8	
	T - 1	11	19	
	Move subjects	4	23	
	S - 2	7	30	
	T - 2	7	37	
	Move subjects	3	40	
	S - 3	7	47	
	T - 3	7	54	
	Move subjects	4	58	
	S - 4	7	65	
	T - 4	8	73	73
Move to recovery room		6		
Recovery	S - 1	7	7	
	T - 1	11	18	
	Move subjects	4	22	
	S - 2	7	29	
	T - 2	7	36	36

*A cycle consists of one pair of sensitivity ('S') and tracking ('T') Measurements.

**Reported to the nearest minute.

of tests with a minimum of delay between each subject's completion of the control series and his first cycle in the experimental series. This delay averaged 10 minutes.

4. Experimental Series

The experimental series consisted of 4 cycles of measurements carried out under the temperature conditions required by the research design. Apparatus and subjects were moved to the control room so as to minimize the delay between measurements of the experimental and recovery series. This delay averaged 6 minutes for all groups.

5. Recovery Series

Two cycles of measurements were carried out during the recovery series, the order of measurements being the same as that previously followed. After completion of this series the condition of the thermocouples was checked and the subjects dismissed. All equipment and apparatus was stowed in readiness for the next day's research.

F. Checks on the Methods of Measurement

There are certain checks which are important in any attempt at objective measurement. Manv of the previous studies to which the present research is related did not report such checks and, consequently, the interpretations of their results are not as unambiguous as they might have been. Before reporting results of the present study, it seems important to give some answers to the following two questions: How reliable were the various measuring scales? How were they influenced by practice effects?

1. Reliabilities of Measuring Scales

Each measuring scale was applied a sufficient number of times during each cycle to allow for the calculation of correlations between odd and even measurements. Table 8 shows the magnitudes of these correlations, determined by the product moment method. The correlations would be higher if corrected to take into consideration the full lengths of the measures employed. The very consistent trends in the results obtained when the various measures were applied can also be taken as evidence that the measures served their purposes in a satisfactory manner.

TABLE 8
RELIABILITIES* OF MEASURING SCALES

Scale	r
Tactile	0.78
Kinesthetic	0.83
Hand Grip	0.93
Movement Tracking	0.92
Pressure Tracking	0.95

*Product moment correlations between odd and even measurements - control trials.

2. Practice Effects

The results of any research in which the same measures of behavior are applied to a subject on several different occasions may be affected significantly by practice. Such serial effects may be eliminated by giving each subject preliminary training to the point where no further improvement in performance occurs. This precaution was incorporated into the present research design.

Previous investigators have shown that considerable improvement with practice occurs in tracking skills. Therefore, a preliminary experiment was conducted to determine how much practice was necessary to reach a constant level of performance on the tracking skills studied in the present research. Thirty-one subjects were selected in the same way as those serving in the main experiment. Fifteen of these practiced movement tracking and 16, pressure tracking, in an air-conditioned room with a mean dry bulb temperature of 27.8° C. Each subject was given a series of 10-minute practice sessions, the sessions separated by 10-minute rest periods. The effects of practice are shown by Curves 3 and 4 in Figure 8.

EFFECTS OF PRACTICE : TRACKING PERFORMANCE

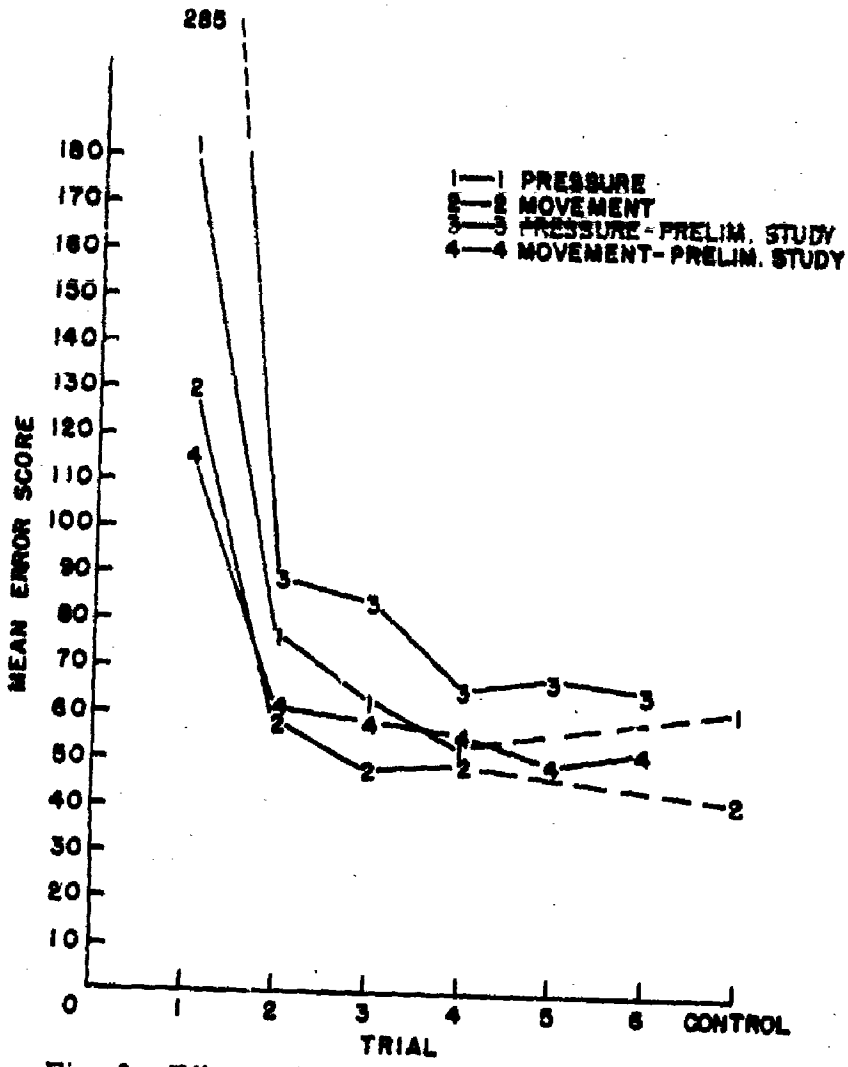

Fig. 8. Effects of practice on tracking performance.

It will be seen that improvement occurred rapidly and a consistent level of performance was reached for both movement and pressure tracking within 4 practice sessions. The duration of the preliminary training period for the main experiment was determined on the basis of these results.

Checks were made on the efficiency with which preliminary training during the main experiment served its purpose. Curves 1 and 2 in Figure 8 show the effects of practice on movement and pressure tracking and Curves 1, 2, and 3 in Figure 9 for the effects of practice on measures of tactile and kinesthetic sensitivity and of hand grip. These curves indicate that consistent levels of performance had been reached before the experimental series of measurements was taken.

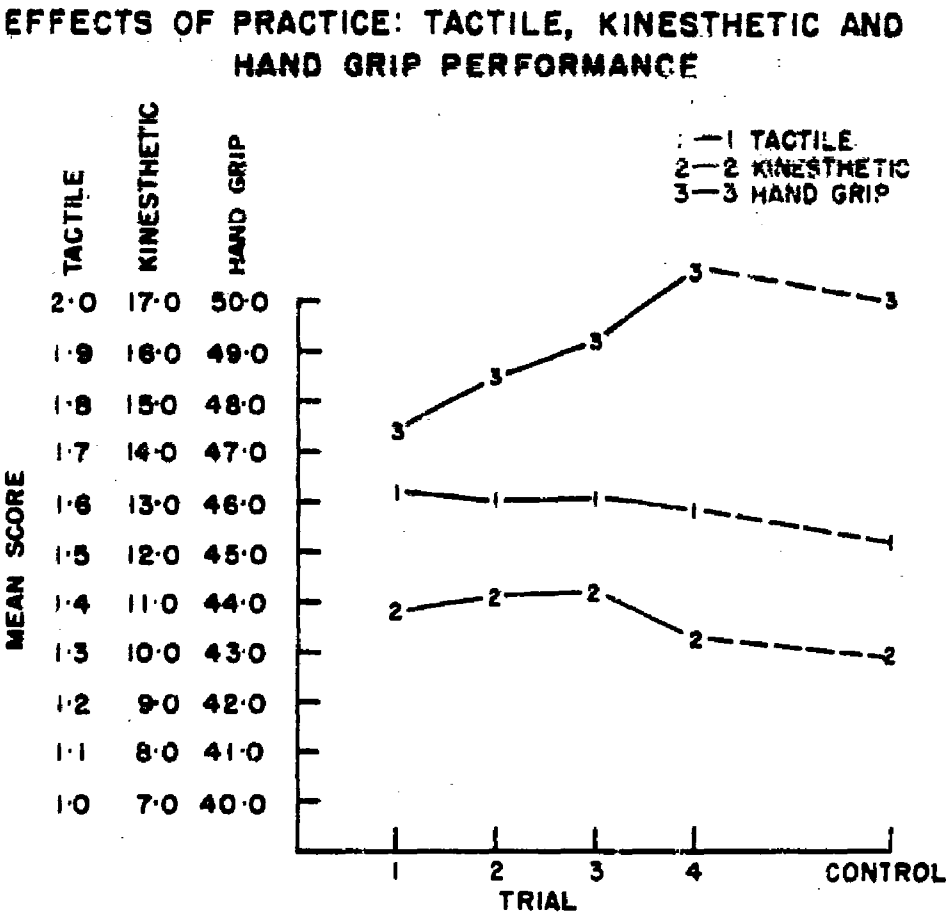

Fig. 9. Effects of practice on tactile, kinesthetic and hand grip performance.

IV. RESULTS

The results are summarized below under several different headings. Most of the analysis has been based upon distribution-free statistics. When statements are made regarding significances of differences or trends, "significance" is defined in terms of the 5% level of confidence.

A. Relations between Performance and Ambient Temperature

Four curves are plotted in each of Figures 10, 11, 12, 13, 14, and 15. They represent the mean performances of the various groups

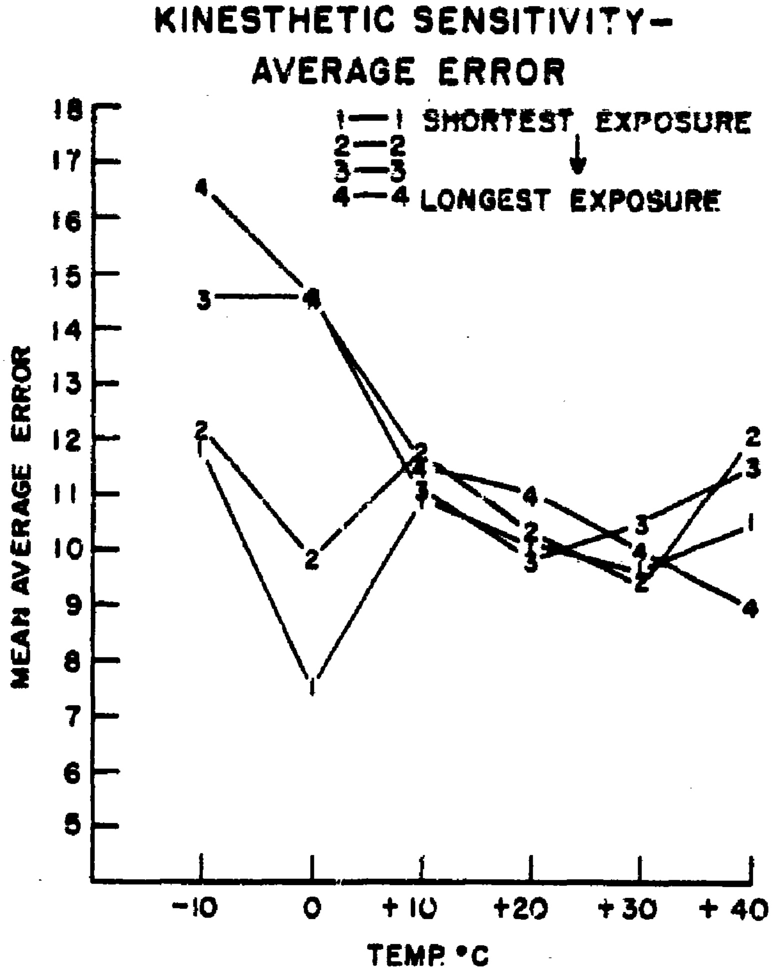

Fig. 10. Kinesthetic sensitivity (average error) as a function of ambient temperature and duration

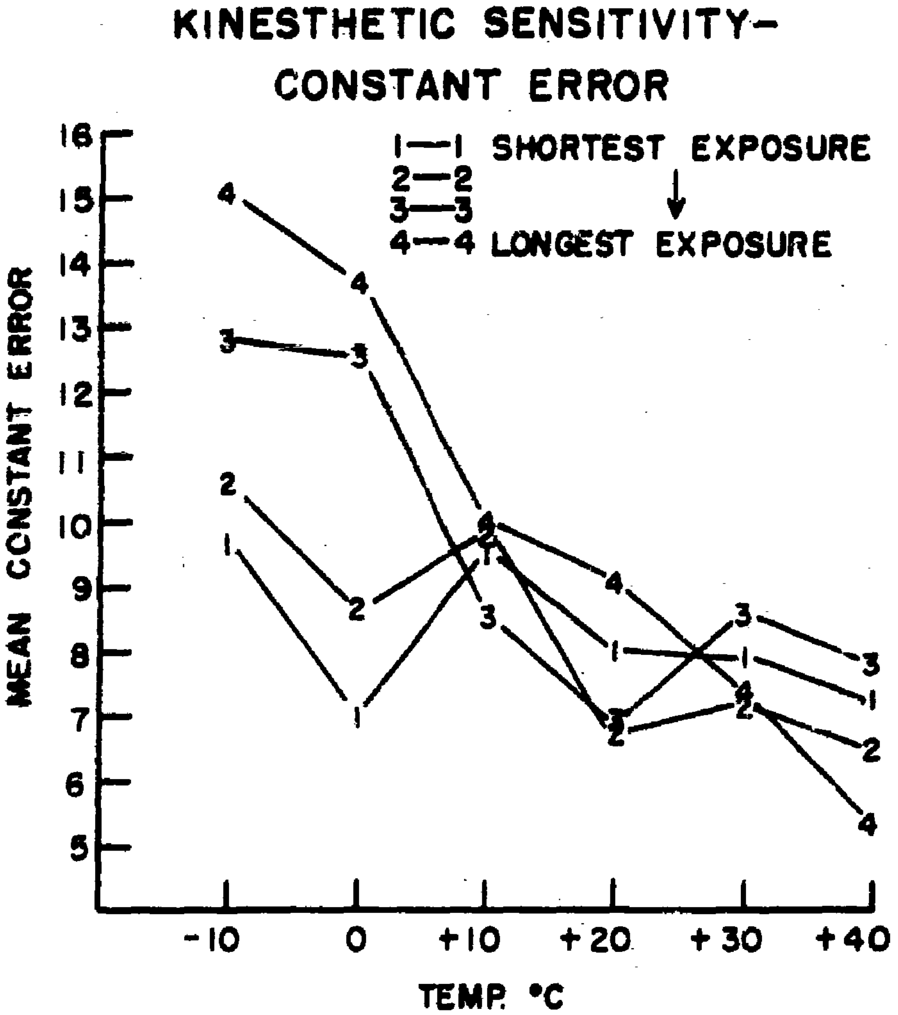

Fig. 11. Kinesthetic sensitivity (constant error) as a function of ambient temperature and duration of exposure.

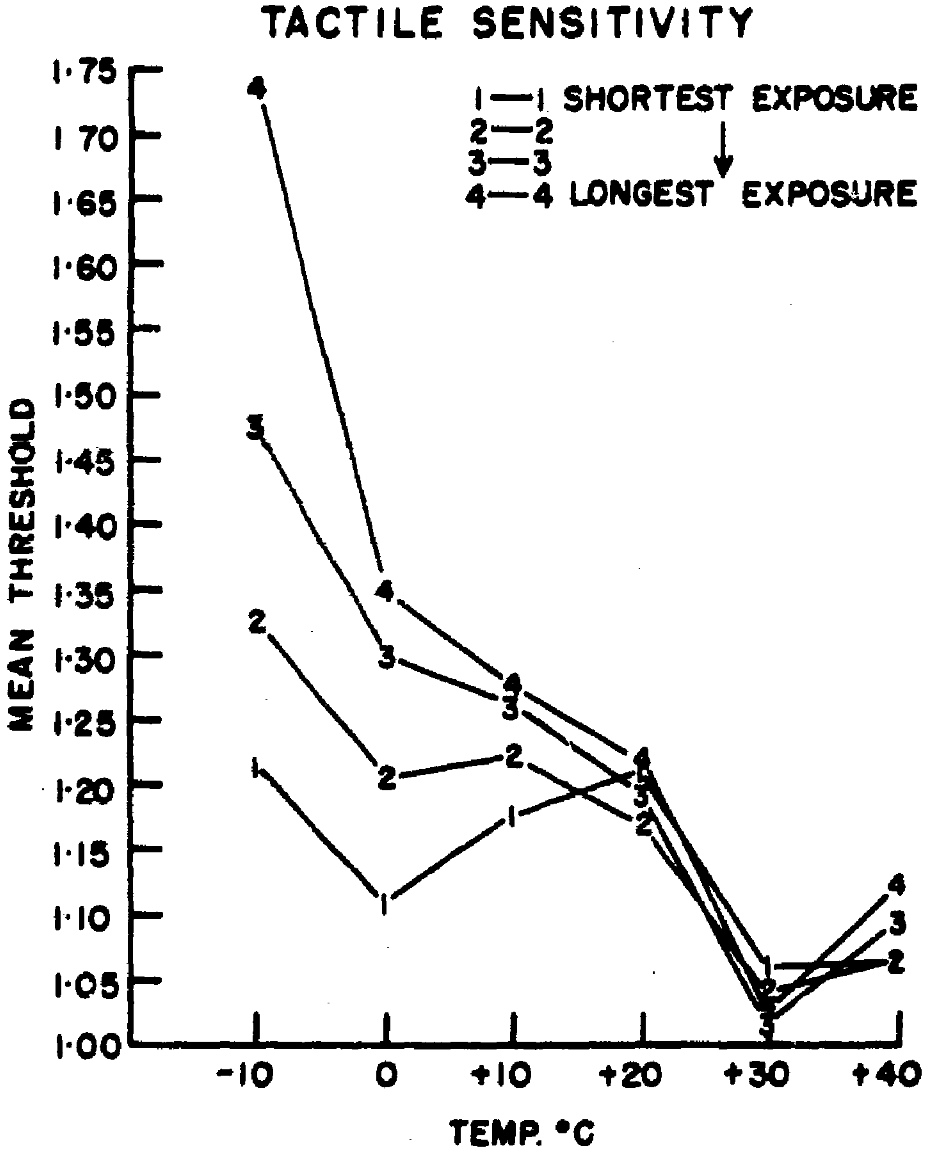

Fig. 12. Tactile sensitivity as a function of ambient temperature and duration of exposure.

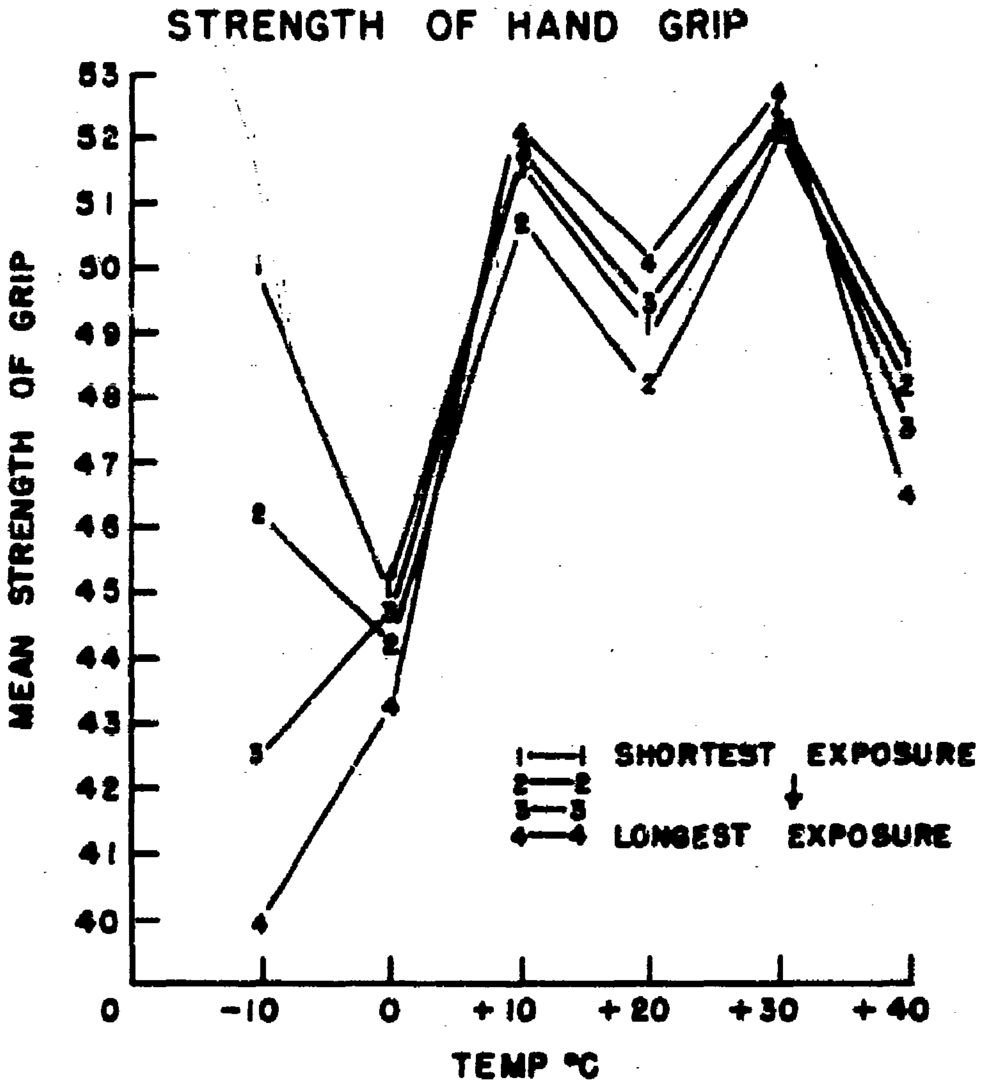

Fig. 13. Strength of hand grip as a function of ambient temperature and duration of exposure.

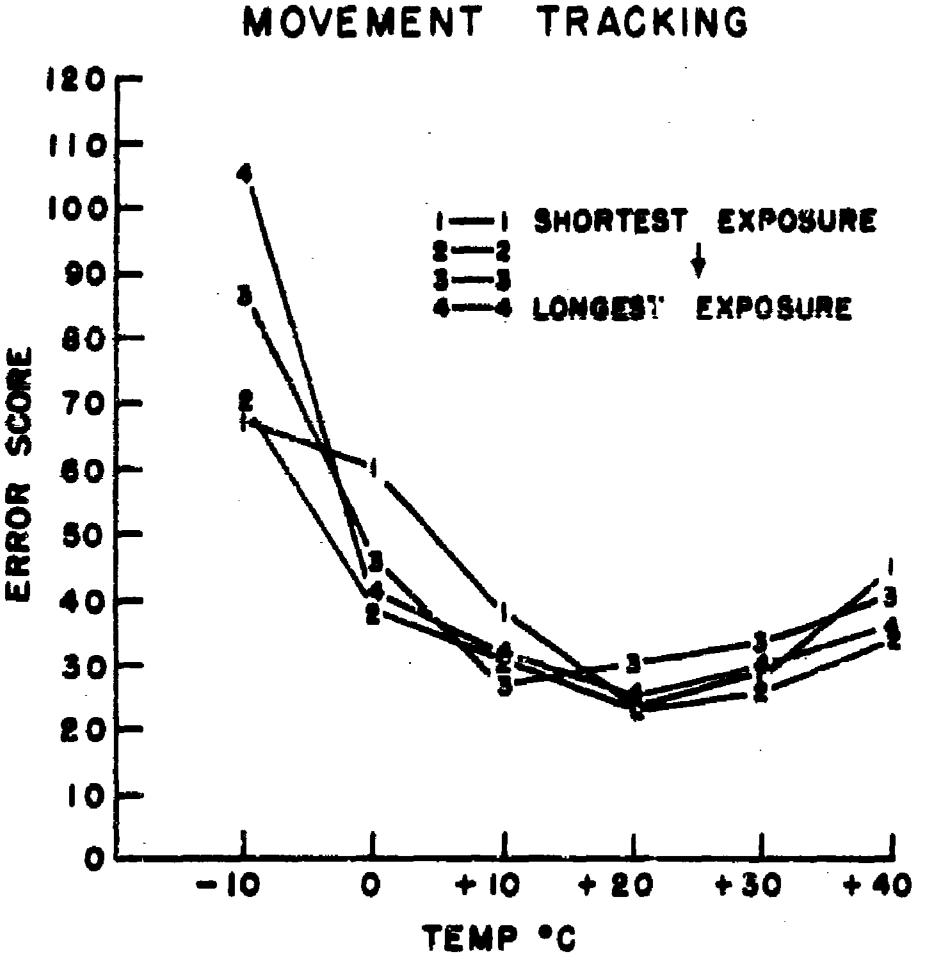

Fig. 14. Movement tracking performance as a function of ambient temperature and duration of exposure.

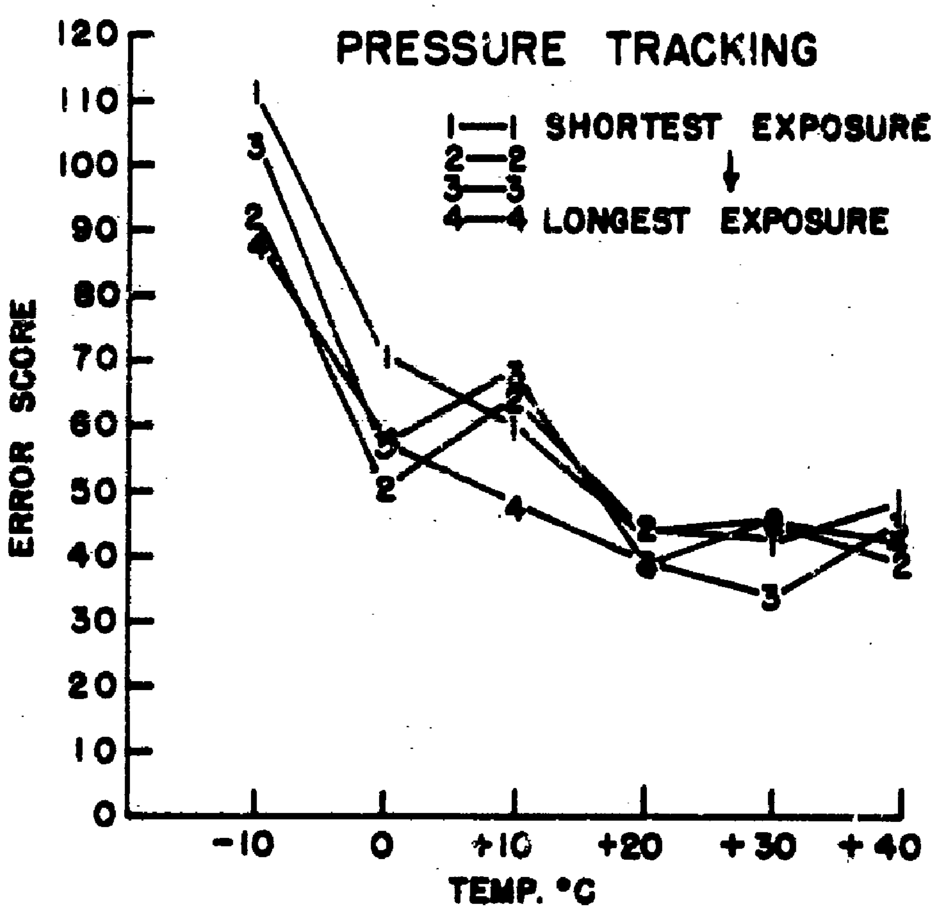

Fig. 15. Pressure tracking performance as a function of ambient temperature and duration of exposure.

at different durations of exposure to their respective experimental temperatures, ranging from 1, the shortest exposure, to 4, the longest. The actual durations of these exposures, given in minutes, are shown in Table 7. The temperatures on the abscissa are in terms of dry-bulb measurements. Inspection of these curves reveals certain systematic relations between performance and temperature. For example, Curves 1 and 2 in Figures 10 and 11 suggest that the range of temperature to which the subjects were exposed had little or no systematic effect on kinesthetic sensitivity where the exposure was of short duration. Curve 3 shows the beginning of a decrement in performance at the low end of the scale, but still a relation between temperature and sensitivity is not clearly apparent. The relation becomes obvious in Curve 4 where decreasing temperature appears to be highly and positively related to decreasing sensitivity. Examinations of Figures 12, 13, 14, and 15 suggest that significant relations also existed between temperature and the other performances measured in the present study, 2 new points arising which are worthy of particular attention. First, a systematic temperature effect appears to occur with shorter durations of exposure in the cases of tactile sensitivity, and the 2 measures of tracking than in the other performances. Second, there is a suggestion in Figures 12, 13, and 14 that the relation between temperature and performance may be curvilinear, decrements occurring at both the cold and hot ends of the temperature scale.

These observations, based on inspection of the curves relating temperature and performance, were examined by statistical analyses of the experimental data and the results are reported in Tables 9, 10, and 11. From Table 9 it is clear that significant trends existed between temperature and all forms of performance when the duration of exposure to the experimental temperatures was at its maximum. Some measures of performance were more sensitive to temperature than others. Thus pressure tracking was significantly related to temperature at all 4

TABLE 9

SIGNIFICANCES* OF RELATIONS BETWEEN PERFORMANCE AND AMBIENT TEMPERATURE

Duration of Exposure	Kinesthetic-A.E.	Kinesthetic-C.E.	Tactile	Hand Grip	Movement Tracking	Pressure Tracking
1	0.29	0.53	1.47	-0.84	2.10**	3.74**
2	0.02	1.34	3.32**	-1.45	1.80	2.85**
3	1.93	1.67	4.25**	-1.93	1.66	3.90**
4	2.88**	2.87**	4.81**	-2.50**	2.21**	2.77**

*Given in terms of 'z', calculated by Jonckheere's method (25).

**Values significant at the 5% level of confidence or better.

TABLE 10

CORRELATIONS* (τ) BETWEEN MEASUREMENTS OF PERFORMANCE AND AMBIENT TEMPERATURE

Duration of Exposure	Kinesthetic-A.E.	Kinesthetic-C.E.	Tactile	Hand Grip	Movement Tracking	Pressure Tracking
1	-0.03	-0.05	-0.14	-0.08	-0.29**	-0.50**
2	-0.002	-0.13	-0.31**	+0.14	-0.24	-0.38**
3	-0.18	-0.16	-0.40**	+0.18	-0.22	-0.52**
4	-0.25**	-0.27**	-0.43**	+0.23**	-0.52**	-0.35**

*The signs of the correlations indicate impairments in performances with decreasing temperatures.
**Values significant at the 5% level of confidence or better.

durations of exposure and tactile sensitivity at all but the shortest duration. The magnitudes of these relations are shown in Table 10 where they are expressed in terms of the rank correlation coefficient "Tau."

Not only is it important to know that significant relations did exist between temperature and performance, it is also essential to understand the form which these relations took. Inspection of Figures 10, 11, and 15 indicates that for both measures of kinesthetic sensitivity and for pressure tracking, performance was progressively impaired as temperature decreased below +20° C, but that no significant effects of temperature appeared above this level. The other performances seem to have been affected somewhat differently. As with kinesthetic sensitivity and pressure tracking, impairment of performance increased at the cold end of the temperature scale, but impairment also began to appear at the high temperature end. If these relations were truly curvilinear they would have to be analyzed in terms of different statistics than those reported above. Table 11 contrasts the appropriate "Tau" coefficients from Table 10 with correlation ratios without bias, "Epsilon," (26) calculated using the same raw data. Epsilon, which

TABLE 11

CORRELATIONS* (τ and ϵ) FOR RELATIONS BETWEEN EXPERIMENTAL TEMPERATURES AND PERFORMANCE OF TACTILE SENSITIVITY, HAND GRIP TRACKING TASKS

Duration of Exposure	Tactile Sensitivity		Hand Grip		Movement Tracking	
	τ	ϵ	τ	ϵ	τ	ϵ
1	0.14	0.28	0.08	0.13	0.29**	0.54**
2	0.31**	0.52**	0.14	0.17	0.24	0.55**
3	0.40**	0.58**	0.18	0.34**	0.22	0.67**
4	0.43**	0.62**	0.23**	0.44**	0.32**	0.63**

*Methods for computing τ and ϵ were those suggested by Jonckheere (24) and Kelley (26), respectively.
**Correlations significant at the 5% level of confidence or better.

takes into consideration the curvilinearity of the relations, indicates significant association between temperature and movement tracking which did not appear in the earlier analysis. Where relations are significant in Table 11 the magnitudes of the correlation ratios are also substantially higher than were the tau coefficients.

Table 12 summarizes the temperature ranges over which the various performances were most effective. It will seen that tactile sensitivity was most susceptible to variations in ambient temperature, signs of impairment appearing at experimental temperatures on both sides of an optimal point at +30° C. This conforms with other information to be reported later which indicates that tactile sensitivity was impaired after short exposures to the experimental temperatures and also recovered rapidly under the control temperature conditions. The other performances showed no signs of decrement over ranges of 20° in the experimental temperatures. Measures of kinesthetic sensitivity and of pressure tracking were not impaired between +20° and 40° C, although they were affected at the lowest experimental temperatures and might have been at temperatures higher than those to which subjects in the present study were exposed. Measures of hand grip and movement tracking were at their best over the range +10° to +30° C, showing decrements as the experimental temperatures increased or decreased beyond these levels.

TABLE 12

TEMPERATURE RANGES OF EFFECTIVE PERFORMANCE

Performance	Ranges	
	+ °C	+ °F
Kinesthetic - Average Error	20° - 40°	68° - 104°
Kinesthetic - Constant Error	20° - 40°	68° - 104°
Tactile	30°	86°
Hand Grip	10° - 30°	50° - 86°
Movement Tracking	10° - 30°	50° - 86°
Pressure Tracking	20° - 40°	68° - 104°

B. Relations between Performance and Duration of Exposure to Experimental Temperatures

It is a reasonable hypothesis that, if exposure to a particular ambient temperature does affect performance, this effect will become more pronounced as the length of the exposure increases. This relation need not be linear and it may hold only within limits, e.g., until an asymptote in performance is reached. Examination of Figure 10 supports this prediction. For the 2 lowest temperatures kinesthetic sensitivity, as measured by the mean average error, decreases systematically as duration of exposure increases. This is seen clearly from the rank orders of points on the 4 curves, which go from smallest average error at Point 1 to largest average error at Point 4. For the 4 other temperatures the rank orders are scrambled, suggesting a lack of relations between length of exposure and performance. Similar examinations of Figures 11 to 15, inclusive, suggest that, with the exception of movement and pressure tracking, duration of exposure to certain temperatures is related to the magnitude of the decrement in performance

In order to determine how significant these relations were, the data were analyzed using Jonckheere's (24) method. The results are shown in Table 13, where an asterisk has been placed by all values significant at the 5% level of confidence or better. These results support the impressions gained from examination of Figures 10 to 15, inclusive, and emphasize 2 main points. First, with the limits of the present research, neither movement nor pressure tracking is affected in any systematic way by the length of time subjects are exposed to ambient temperatures ranging from -10° to +40° C. Second, at low temperatures kinesthetic and tactile sensitivity and strength of hand grip are affected detrimentally, decrements in performance being positively

TABLE 13

SIGNIFICANCES* OF RELATIONS BETWEEN PERFORMANCE AND DURATION OF EXPOSURE TO EXPERIMENTAL TEMPERATURES

Temp. °C	Kinesthetic-A.E.	Kinesthetic-C.E.	Tactile	Hand Grip	Movement Tracking	Pressure Tracking
+40	-2.84**	-0.68	+0.29	-2.05**	-0.70	+0.70
+30	+0.98	-0.69	-2.25**	-0.49	+0.42	+0.42
+20	-0.49	+0.29	-1.66	+0.88	+0.14	-1.26
+10	-0.69	-0.29	+1.27	-0.49	-0.97	-0.42
0	+3.42**	+2.64**	+2.84**	-3.23**	-2.08**	-1.53
-10	+2.25**	+2.05**	+3.62**	-6.56**	+1.81	-0.70

*Given in terms of 'z' calculated by Jonckheere's method (24).

**Values significant at the 5% level of confidence or better .

related to duration of exposure. There also is some evidence that a similar relation holds for strength of hand grip at high temperature.

C. Recovery from Exposure to Different Ambient Temperatures

The experimental procedure included 2 cycles of measurements following return of the subjects to the control room. This was planned in order to obtain some information regarding recovery from the effects of exposure to the different experimental temperatures. Mean performances during the final experimental and the 2 recovery trials are presented in Table 14. The final column of this table shows the overall recovery in terms of differences between performances on the final experimental and second recovery trials.

The general trend of the results are in the expected directions and 3 main points can be emphasized. First, since recovery implies a previous impairment it would be predicted that the most pronounced evidence of recovery would be found at the 2 lowest temperatures, which have already been shown to produce the greatest impairment in all the performances studied. Inspection of the final column in Table 14 gives general support to this expectation. In this column a negative value indicates an improvement in performance, except for hand grip in which improvement is represented by positive values. Perhaps the clearest illustration of this general trend is to be found in the case of tactile sensitivity. Here there is no apparent improvement at the first 4 temperatures, but the evidence for improvement is statistically significant at better than the 5% level of confidence for groups previously exposed to 0° and -10° C. Further examination of Table 14 reveals a second major point. Performance of hand grip and movement tracking show improvement occurring in groups previously exposed to high as well as low temperatures. Again this is what we would expect since both these types of performance were shown in preceding sections to be impaired at both ends of the temperature range used in this study. A third main point concerns the final level of recovery attained under the present conditions. In no case except tactile sensitivity was the recovery period sufficiently long for impairment following exposure to the extreme temperatures to disappear completely. It will be remembered that tactile sensitivity was affected after relatively short exposures to the experimental temperatures. The evidence now suggests that this sense modality also recovered very rapidly.

TABLE 14

PERFORMANCES ON CONTROL, FINAL EXPERIMENTAL ON RECOVERY TRIALS

Temp. °C	E-4	R-1	R-2	Difference: R2 minus E4
	1. Kinesthetic (Average Error)			
+40	8.92	9.33	9.98	1.06
+30	9.90	9.72	7.98	-1.92
+20	11.04	13.07	10.71	-0.33
+10	11.49	11.38	9.78	-1.71
0	14.63	11.99	12.72	-1.91
-10	16.77	13.72	12.30	-4.47
	2. Kinesthetic (Constant Error)			
+40	5.43	5.80	5.07	-0.35
+30	7.37	8.07	6.01	-1.36
+20	9.23	11.50	6.89	-2.34
+10	9.93	9.43	6.82	-3.11
0	13.74	10.03	10.72	-3.02
-10	15.07	9.45	8.75	-6.32
	3. Tactile			
+40	1.13	1.18	1.17	0.04
+30	1.03	1.03	1.03	0.00
+20	1.22	1.21	1.22	0.00
+10	1.22	1.23	1.30	-0.08
0	1.35	1.20	1.14	-0.21
-10	1.75	1.25	1.23	-0.52
	4. Hand Grip			
+40	46.60	50.19	50.44	3.84
+30	52.46	51.71	52.98	0.52
+20	50.31	50.52	51.77	1.46
+10	52.04	53.13	51.63	-0.41
0	43.48	43.77	45.79	2.31
-10	40.08	41.31	46.27	6.19
	5. Movement Tracking			
+40	36.33	38.50	28.67	-7.66
+30	30.17	26.83	23.00	-7.17
+20	24.50	21.83	20.67	-3.83
+10	32.33	63.00	33.50	1.17
0	39.50	48.50	32.83	-6.67
-10	106.00	108.17	67.67	-38.33
	6. Pressure Tracking			
+40	43.50	35.83	42.83	-0.67
+30	44.50	56.00	40.67	-3.83
+20	39.00	68.50	36.17	-2.83
+10	48.83	62.83	66.83	18.00
0	56.50	55.17	54.33	-2.17
-10	88.83	105.83	74.83	-14.00

*Negative values indicate improvement in performance, except for hand grip in which improvement is represented by positive values

D. Relations between Skin Temperature and Ambient Temperature

Figures 16, 17, 18, 19, 20, and 21 show the changes in mean skin temperatures of the various groups during the course of the control, experimental, and recovery phases of the research. The main features of these curves may be described as follows.

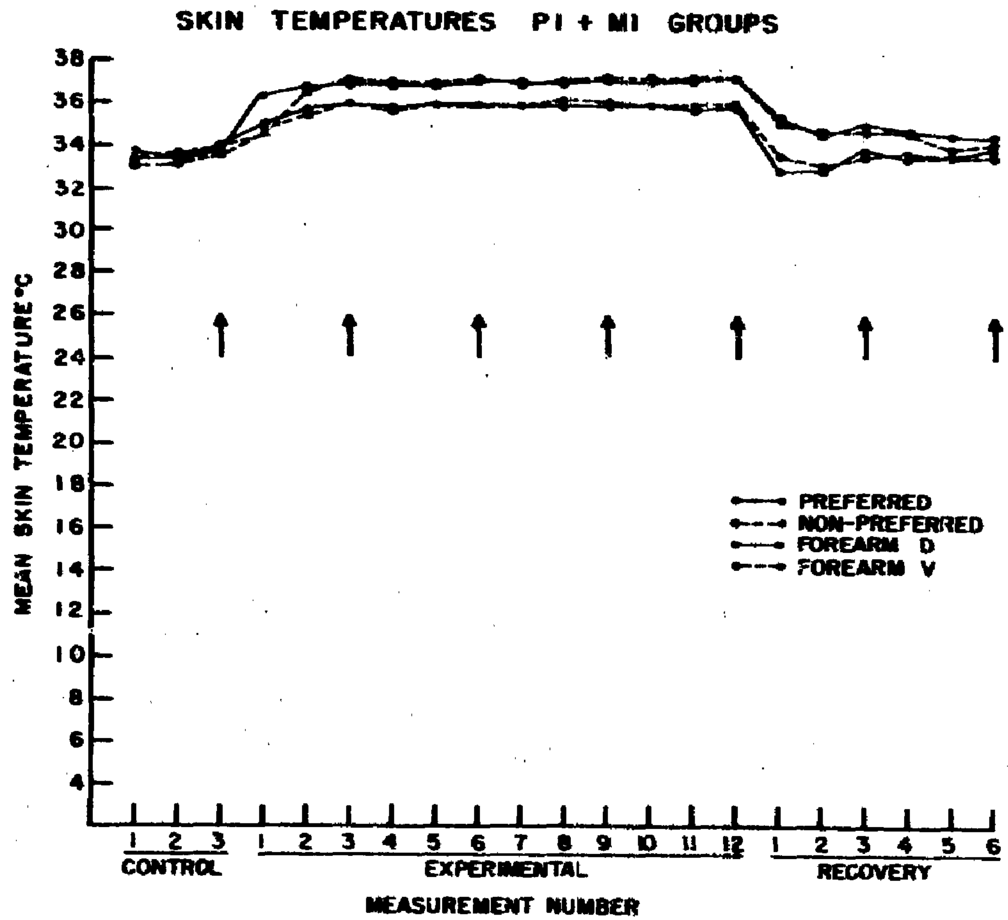

Fig. 16. Effects on skin temperatures of exposure to ambient temperature of +40° C.

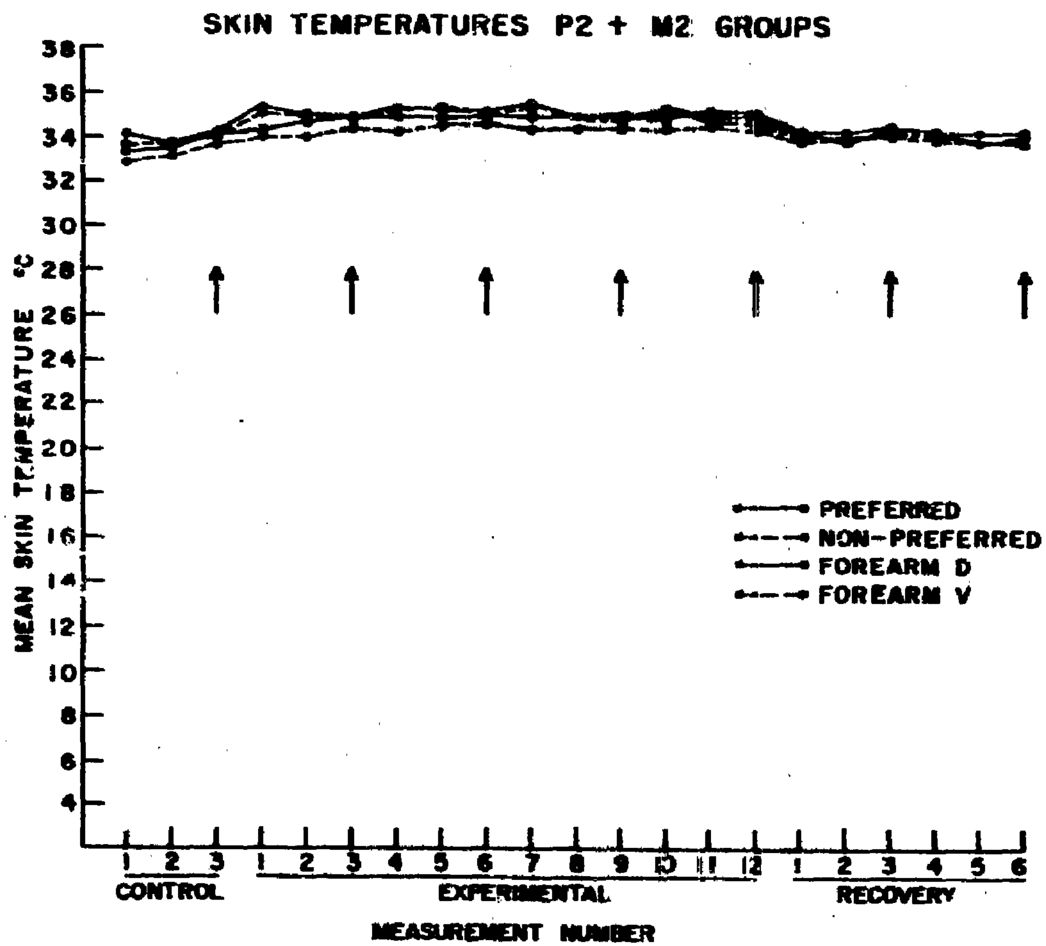

Fig. 17. Effects on skin temperatures of exposure to ambient temperature of +30° C.

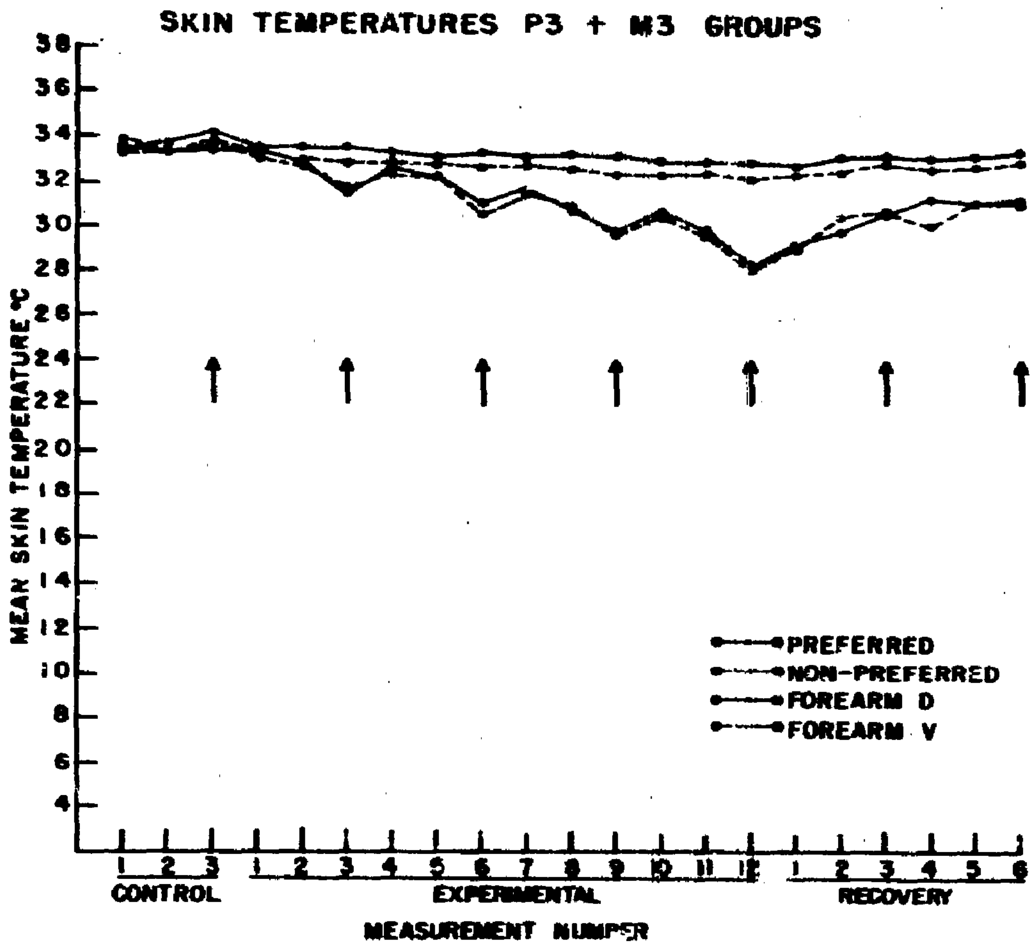

Fig. 18. Effects on skin temperatures of exposure to ambient temperature of +20° C.

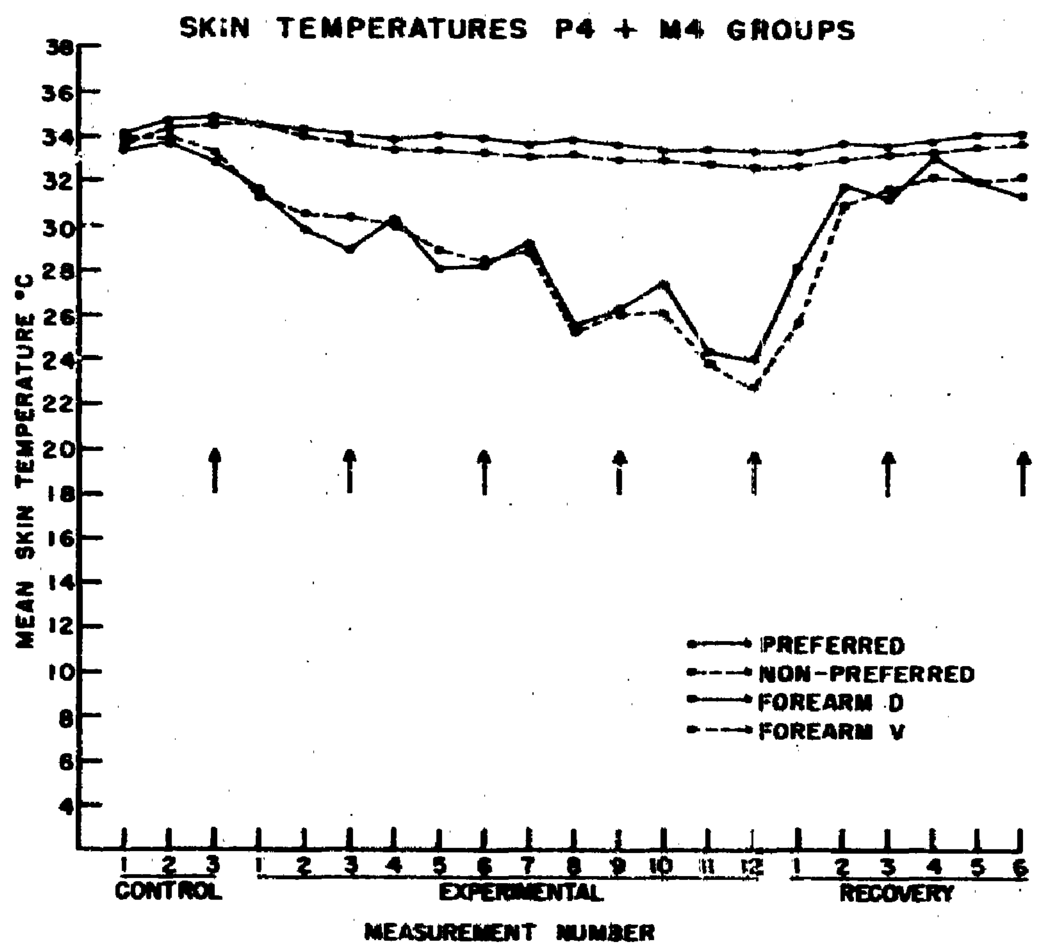

Fig. 19. Effects on skin temperatures of exposure to ambient temperature of +10° C.

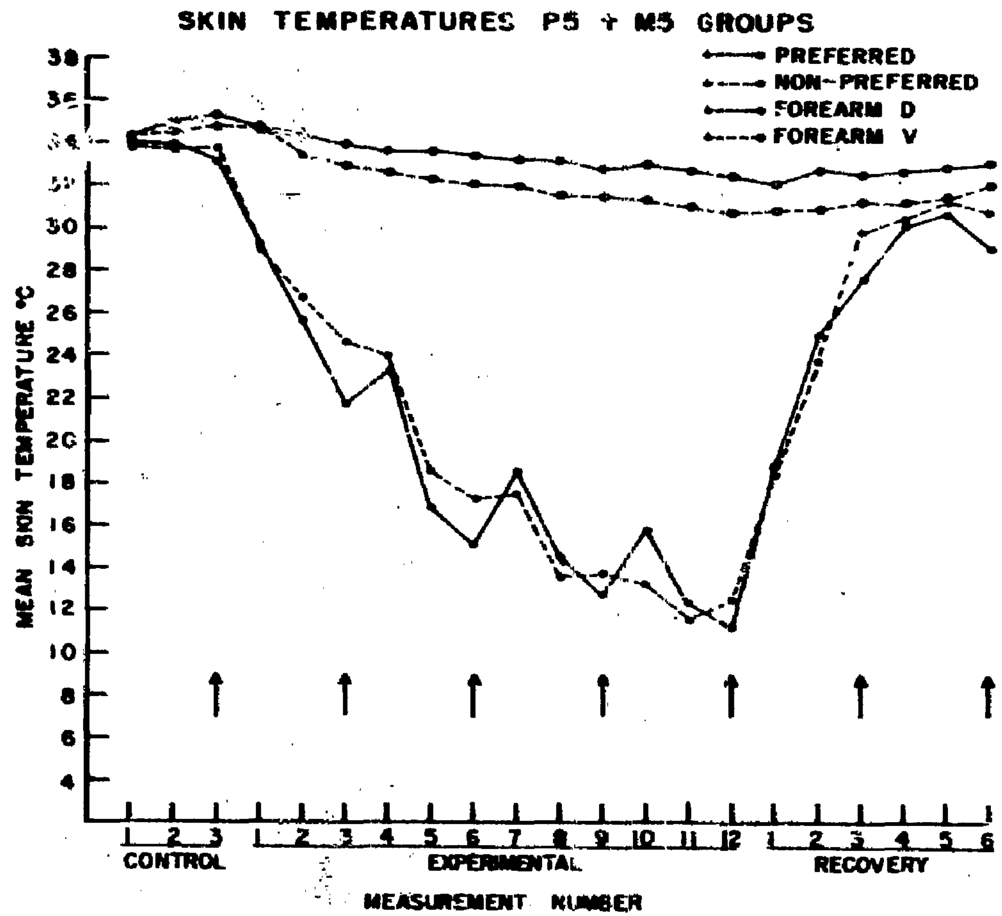

Fig. 20. Effects on skin temperatures of exposure to ambient temperature of 0° C.

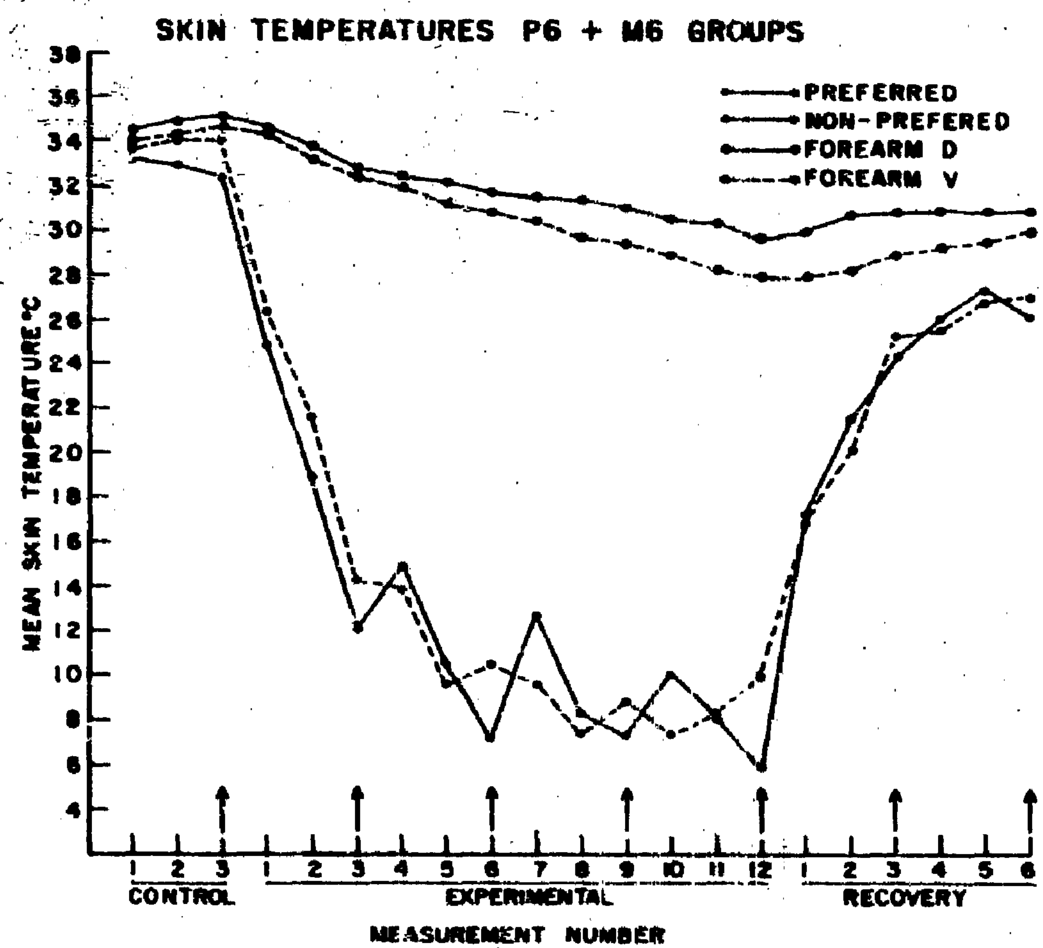

Fig. 21. Effects on skin temperatures of exposure to ambient temperature of -10° C.

1. Temperature of Fingers

Skin temperature remained at a constant level of 33° to 34° C during the control series. Changes in skin temperatures appeared in the first measurements following exposure to the various experimental temperatures. These changes were most striking in subjects exposed to the temperatures +20° C and below. Skin temperature dropped more rapidly and reached a lower terminal point the colder the ambient temperature. At -10° and 0° C the drops were rapid initially and then tended to level off at about 8° and 14° C, respectively. Skin temperatures during the recovery series rose rapidly at first and leveled off as the temperatures of the control series were approached. The maximum level reached during the 36 minutes of the recovery series was a function of the ambient temperature to which the subjects had been exposed, higher levels of recovery being associated with higher ambient temperatures. Skin temperatures at +30° C changed relatively little, but at +40° C they showed a rise which dropped toward the levels of the control series during recovery. Thus, as would be predicted, the magnitudes of changes in skin temperature during both the experimental and recovery series are shown to have been functions of the duration of exposure to the respective ambient temperatures.

Figure 22 shows the relations between the experimental temperatures to which the subjects were exposed and the final levels of skin temperature. It is apparent that a high relation existed between the two. This is confirmed by the results of statistical analyses summarized in Table 15, where the Tau correlations for the preferred and non-preferred hands are shown to be 0.96 and 0.92, respectively. Such high correlations facilitate the general analysis of the experimental data, for they indicate that relations between measures of the various performances and skin temperature were similar to those between the performances and ambient temperature as described above.

2. Temperature of Forearm

The temperatures recorded by thermocouples attached to the dorsal and ventral surfaces of the forearm showed similar changes, but of much less magnitude, despite the fact that this part of the body was covered with protective clothing. The Tau correlations between ambient temperature and final skin temperature readings as shown in Table 15 are 0.83 and 0.87 for the dorsal and ventral surfaces, respectively. These correlations indicate highly significant trends in the direction of decreasing skin temperatures with decreasing ambient temperatures.

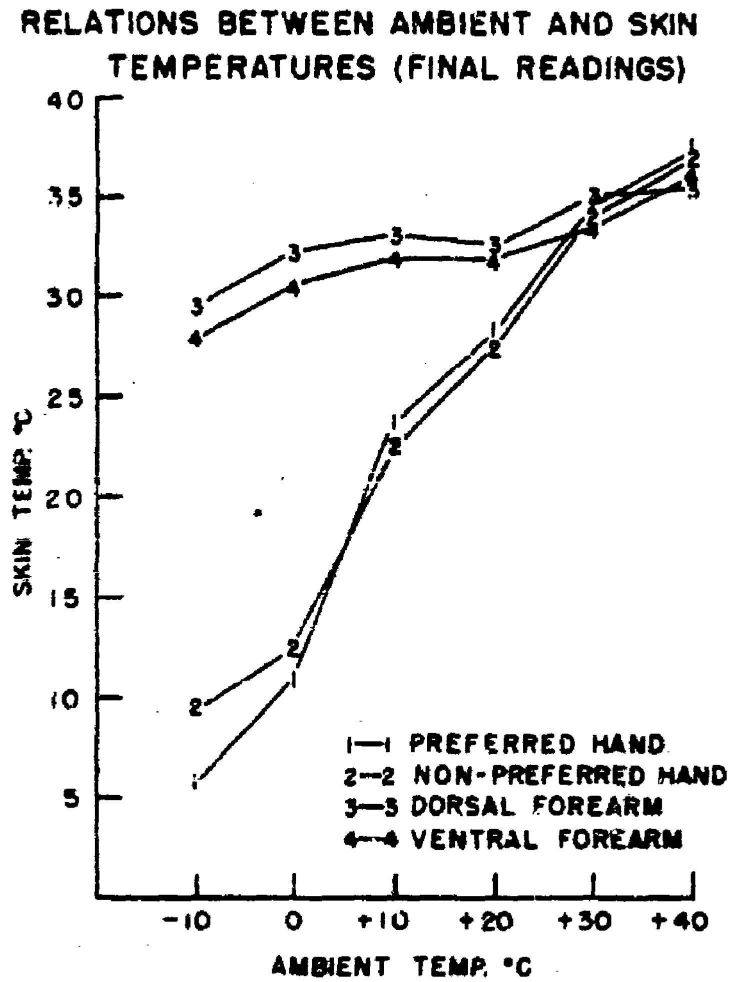

Fig. 22. Relations between ambient and skin temperatures (final readings).

TABLE 15

SIGNIFICANCES OF RELATIONS BETWEEN AMBIENT AND SKIN TEMPERATURES (FINAL LEVEL)

Position of Thermocouple	S	Z*	r
Preferred hand	2062	10.18	0.96
Non-preferred hand	1992	9.83	0.97
Dorsal forearm	1802	8.89	0.80
Ventral forearm	1876	9.26	0.87

*These values are all very highly significant. They have been calculated using Jonckheere's method (25).

One feature of the forearm temperatures which deserves particular emphasis was the tendency for the ventral surface to change temperature more rapidly than the dorsal surface as duration of exposure to the more extreme ambient temperatures increased. This tendency is apparent from an inspection of Figures 16, 19, 20, and 21, but it shows up more clearly in Table 16, which presents rank correlations between the differences in forearm temperatures and duration of exposure. The high correlations obtained at +40°, +10°, 0°, and -10° indicate that the magnitude of the differences increased consistently as length of exposure to these ambient temperatures increased.

TABLE 16

CORRELATIONS* BETWEEN DIFFERENCES IN FOREARM SKIN TEMPERATURES AND DURATION OF EXPOSURE TO EXPERIMENTAL AMBIENT TEMPERATURES

Group	Ambient Temp, °C	'P'
M1 + P1	+40	-0.88**
M2 + P2	+30	+0.24
M3 + P3	+20	+0.39
M4 + P4	+10	+0.92
M5 + P5	0	+0.94
M6 + P6	-10	+0.92

*Computed by rank-difference method.

**At this ambient temperature the forearm warmed with increasing exposure; in all other instances, it cooled.

E. Effects of Contact with Metal Control Surfaces on Skin Temperature

During the present experiment great care was taken to prevent both of a subject's hands from contacting surfaces which might affect skin temperature. The only exception to this rule was a deliberate one and occurred during the time in each cycle of measurements when the subject was performing at the tracking task. During each of these 5-minute periods he grasped a brass knob at the top of the control column with the fingers of his preferred hand, the non-preferred hand not contacting any surface. Separate knobs were used for the experimental and control rooms and were kept in those rooms during the entire period of experimentation with the different temperature groups. The actual temperatures of these knobs determined at the beginning and end of each day's operations in the 2 rooms, are summarized in Table 17. The only knob temperature above normal body temperature was the one used during the experimental phase of the research by the groups exposed to an ambient temperature of +40° C. During the experimental series at this ambient temperature the knob temperature decreased by one degree and at all other temperatures it increased from 4 to 6 degrees.

TABLE 17

KNOB TEMPERATURES* AT THE BEGINNING AND END OF EXPERIMENTAL AND RECOVERY PHASES

	Experimental Phase			Recovery Phase		
Group	Ambient Temp. °C	Beginning	End	Ambient Temp. °C	Beginning	End
M1 + P1	+40	+39	+38	+24	+28	+30
M2 + P2	+30	+30	+32	+25	+27	+31
M3 + P3	+20	+21	+25	+24	+25	+28
M4 + P4	+10	+12	+18	+22	+21	+24
M5 + P5	0	+ 4	+ 9	+23	+21	+25
M6 + P6	-10	+ 4	+ 2	+23	+18	+23

*To nearest degree

With these facts in mind it is worthwhile to look again at Figures 16 to 21, inclusive, which show skin temperatures during the control, experimental and recovery phases of the research for the 6 different temperature groups. Arrows indicate skin temperatures recorded immediately following completion of performance of the tracking task. Inspection of the curves for the 2 lowest temperature groups clearly shows that contact with the brass control knob had a systematic effect on the skin temperature of the preferred as compared with the non-preferred hand. In all instances skin temperature of the former was lower than that of the latter immediately after the knob was released. This lowering of skin temperature was always followed by a marked re-warming of the preferred hand and then a cooling until the next re-warming took place. This systematic cycle of events did not occur at temperatures of +10° C and above, where the skin temperature of the preferred hand was fairly consistently above that of the non-preferred. These are phenomena which may well have implications for the design of equipment to be used at low environmental temperatures.

V. DISCUSSION

When we speak of "efficiency" in military or industrial operations we usually mean the efficiency of a man-machine system, even though the machine in many cases may be a very simple one. Such combinations operate in environments which may affect man's performance and thus the efficiency of an entire system. The present research was designed to study the effects of changes predominantly in one major environmental variable, ambient temperature, on certain types of human performance. It would appear worthwhile to discuss the results of the research in terms of their implications for human performance and machine design.

A. Human Performance

A report (19) from the Armored Medical Research Laboratory, referred to earlier in this paper, contains the very significant statement that -20° F with zero wind velocity "... was considered to be the lowest temperature at which both the personnel and the vehicular equipment of the Armored Command would be able to function without the occurrence of serious breakdowns." These atmospheric conditions are not nearly as extreme as those which could be expected during the course of extended sub-arctic operations. Regardless of its precision, the statement points clearly to the limitations which environmental conditions may place upon the efficiency of man-machine systems used by the military services. The discussion which follows attempts to examine the results of the present research from the point of view of how exposure to high and low ambient temperatures may affect the human element in such systems.

1. Tactile Sensitivity

Many of the skills which military personnel are required to perform depend upon good tactile sensitivity in the fingers and any interference with this sensitivity may result in impairment of performance. Previous research (32, 33, 2) has been confirmed by results of the present study in showing that, as ambient and skin temperatures decrease, tactile sensitivity also decreases. It would be expected that such decrements would be associated with impairment in the performance of tasks involving the use of sensory input from the fingers and, indeed, such relationships have been reported. The conventional approach to maintaining normal skin temperature of the hands during exposure to cold has been the use of protective covering in the form of gloves or mittens, but such covering itself interferes with tactile sensitivity and performance (16). Some of this impairment can be overcome by practicing with mittened or gloved hands the skills that may eventually have to be performed in the cold (18). However, the problem is still not solved for there is evidence that "the best glove combinations now available... are not capable of either keeping the hands warm or maintaining their functional efficiency" (19). We must look for some other technique for preventing this impairment of performance, a search perhaps better discussed under matters of machine design.

Previous research has been concerned with the effects of cold on tactile sensitivity, but results of the present research suggest that impairment of sensitivity also occurs under the influences of high temperatures. In fact, the temperature range for maximum tactile sensitivity appears to be a particularly narrow one. This phenomenon of high-temperature decrement needs further investigation before any more definite statements can be made about its characteristics.

2. Kinesthetic Sensitivity

Basic to man's performance of many skilled activities is his kinesthetic sensitivity. The results of recent research (17) imply "...that skilled movements are continuously regulated by using kinesthetic data which are generated by the limb in motion and are continuously fed back to the higher motor centres." Any interference with this feedback would be expected to result in decrements in performance. It cannot be contended that the technique used in the present investigation for measuring kinesthetic sensitivity involved that modality only. Spragg (50), from whom the technique was borrowed, refers to it as involving "tactual-kinesthetic" cues. Accepting this "contamination" of cues it is apparent from the results reported above that the measures of "kinesthetic" sensitivity in the present investigation were related to variations in ambient temperature in quite a different way than were measures of tactile sensitivity. Kinesthetic sensitivity was affected only at the low temperatures and then after longer exposures than were required to produce impairment in tactile performance.

The present results are of interest even if we prefer to consider them as providing information about skill in the setting of knob controls rather than about kinesthetic sensitivity. Many military skills, such as tuning a radio, adjusting the various controls on a radar, focusing a camera, and adjusting a rangefinder setting, require the accurate setting of knob controls. The present results show that such skills may be affected by exposure to cold and that signs of the resulting impairment, both in average and constant errors, begin at temperatures below +20° C.

3. Strength of Hand Grip

Good manual dexterity and accurate finger movements are also required in the efficient performance of many skills which military personnel must possess. "Cold stiffness" is a very familiar phenomenon, characterized by an impairment of these 2 capacities. Joint temperatures, on exposure to low ambient temperatures, fall significantly, even to a greater extent than muscle, rectal or average skin temperatures. More recently research (22) has demonstrated that the maximum speed of joint movements decreases on exposure to cold. Theoretically performance of a skill, which imposes a load transmitted through the joint or on its sliding surfaces, intensifies the decrement. Study of the viscous properties of synovial fluid bathing a joint has shown an increase of viscosity for a definite fall in temperature and has led to the conclusion that "the characteristics of synovial fluid are sufficient to account for increased forces required to move a joint, for loss in speed of movement and decrement in maximum strength exerted on exposure to cold" (22). The systematic measurement of strength of hand grip in the present study has added information to this general picture. The results support previous findings that performance decrements occur on exposure to cold. They show that decrements are greater the lower the temperature and that signs of impairment appear at temperatures below +10° C. They also indicate that impairment occurs at high temperatures, at temperatures above +30° C. Whether these effects of heat can be accounted for in terms of viscosity changes of the synovial fluid or whether some other mechanism must be involved are matters for further research.

4. Tracking Skill

The controls used in the tracking tasks were only two of several possible types. Operation of the movement control involved displacement of the control column and, hence, isotonic muscular contractions. On the other hand, the pressure control involved very little displacement thus emphasizing muscular contractions of an isometric nature. Gibbs (17), using another type of pressure control in which "... the controlled contractions of muscle were virtually isometric," has compared movement and pressure controls under ordinary temperature conditions. He has reported that "... the pressure control was definitely better when making both discrete and continuous responses, learning was easier, and differential transfer effects appear which also favored this pressure control." Although the type of pressure control used in the present research was not as effective as that used by Gibbs, there still is evidence which suggest that pressure controls may have general advantages when a machine may be operated under both hot and cold conditions. The effective temperature ranges for both movement and pressure tracking covered approximately 20° C, but movement tracking showed signs of impairment at both ends of the temperature range used in the present study while pressure tracking appeared to be affected only at the low end. It is obvious that these results have practical implications for machine design and should be investigated further.

5. Skin Temperature

As would be predicted the correlations between skin temperatures of the hands and the ambient temperatures to which the hands were exposed were found to be very high. Skin temperature was also highly related to the duration of exposure. These results are consistent with observations of other investigators (2, 32, 58, and 59). On the basis of these results we would expect to find that relations between measures of the various performances and skin temperature were similar to those between the performances and ambient temperature, an expectation which is supported by examination of the research data.

Two other general observations arising from the measurements of skin temperature deserve particular attention. The first concerns the effects of contact with metal control surfaces on skin temperature. Measurements during the present investigation revealed a recurrent cycle of skin temperature changes during exposure at the 2 lowest ambient temperatures. Immediately after subjects had released their grasp on brass control knob following a 5-minute tracking period the skin temperature of the preferred hand, used in the performance, was lower than that of the non-preferred or "control" hand. This lowering of skin temperature was always followed by a marked re-warming of the preferred hand and then a cooling until the next re-warming took place. The mechanism of this re-warming would seem to be centered in what has been referred to as "cold-induced vasodilation" (7, 8). Periodically recurring vasodilation has been demonstrated in fingers exposed to cold ambient temperatures both when the body as a whole is chilled or warm as in the present research. The amount of local cooling needed to evoke the response has been shown to be less the warmer the body. It is hypothesized (7) that this vascular phenomenon is dependent upon "... the activation of a local sensory axon reflex." The existence of relations between these cyclic vasodilations and certain sensory events has been indicated by research results showing that sensations of increasing cold and pain from fingers exposed to cold air were "spontaneously relived" with the occurrence of each vasodilation wave. In the present investigation it would appear that the increased loss of heat when subjects were grasping cold control surfaces served to trigger off a vasodilation wave. This cycle of events occurred only at the 2 lowest experimental temperatures where the loss of heat to the control surfaces would be expected to be greatest. It did not occur at ambient temperatures of +10° C and above.

The differences between temperatures recorded from thermocouples on the ventral and dorsal surfaces of the forearm also are of interest. There was a consistent tendency for the ventral surface to change temperature more rapidly than the dorsal surface as duration of exposure to the more extreme ambient temperatures increased. This tendency was clearly apparent despite the fact that the forearm was covered by protective clothing. One possible explanation for this differential cooling lies in the distribution of the venous return from the exposed hand. The veins of the upper arm are divided into 2 sets (23), "superficial" and "deep" which anastamose freely with each other. Most of the blood which supplies the upper limb is returned by the superficial veins, the deep veins being small and inconspicuous. There are 3 main superficial veins on the upper limb, all lying immediately under the skin in the superficial fascia. The cephalic antebrachial vein collects from the radial part of the dorsal venous network of the hand and crosses to the anterior or ventral surface of the forearm. The basilic antebrachial vein arises from the ulnar part of the dorsal venous network of the hand, runs up for some distance on the posterior or dorsal surface of the ulnar side of the forearm, and inclines to the ventral surface below the elbow. The median antebrachial vein draws the venous plexus on the palmar side of the hand, ascends on the front of the forearm and ends in the basilic or median cubital vein. The position of the ventral thermocouple in measuring forearm skin temperature was approximately half-way up the anterior surface on a spot between the cephalic and median antebrachial veins. The dorsal thermocouple was on a spot at some distance from the basilic antebrachial vein. It might be expected that the venous return from the cooling hand would affect skin temperature more rapidly at points where the superficial venous system is more dense, i.e., at points underlying the ventral thermocouple. This hypothesis is entirely consistent with the results obtained in the present study.

6. "Mechanisms" Underlying Impairment

Three of the performances studied in the present investigation showed impairment at both the cold and hot ends of the experimental temperature range. Similar results have been obtained in other studies. In general, performance appears to drop off more significantly at cold than at hot temperatures (52, 53), but the manifestations of the decrements that do occur are similar. It seems important to emphasize, however, that this does not mean that the "mechanisms" underlying impairment at both extremes are the same. As was pointed out in the introduction to this report, the basis upon which ambient temperature exerts its effects on performance may, logically, involve peripheral sensory or motor changes, central perceptual changes, or some combination of these.

B. Machine Design

It is possible to overcome some of these limitations imposed upon human performance by environmental conditions providing that precise information is available regarding the nature of the limitations and that this information is used by those concerned with the design of machines and equipment. Some of these possibilities have been referred to already, but two general points deserve further emphasis.

Before discussing these two points it will be well to make one further comment on the temperature ranges for efficient performance as they have been presented earlier in this report. It will be remembered that these ranges were limited by the first signs of deterioration in performance. For practical purposes of machine design they might be defined differently, e.g., in terms of a temperature and duration of exposure necessary to produce a certain per cent decrement in performance. The limits as stated earlier are, in a sense, ideals which would have to be re-assessed in terms of the technical difficulties in achieving them. It should also be emphasized here that other environmental factors, e.g., air velocity, humidity, and radiant heat, operate with ambient temperature to produce the total effects in any particular situation. The final information needed for machine design should incorporate data on these total effects.

1. Maintenance of Adequate Temperature Levels

Designing machines and equipment to maintain adequate temperature levels can begin only when the temperature ranges of efficient performance are known for the various types of skills which military personnel are required to perform. With such information available two general approaches to solving the problem may be tried. The first involves the design of protective clothing which will maintain temperature within the critical range for as long a duration as possible and yet will interfere as little as possible with the sensory and motor requirements for efficient performance. This suggests a 2-phase testing program for protective clothing: first, tests for effects on basic skills under temperature conditions which produce little or no impairment of performance without the clothing and, second, similar tests under more extreme temperature conditions. These tests should examine the possibility that training while wearing protective clothing may significantly reduce the adverse effects caused by the clothing.

The second general approach to solving the problem of maintaining adequate temperature levels involves the design of machines on which man will be operating. One obvious possibility lies in controlling the temperature of the work space, but this creates very serious technical difficulties particularly when the space is not fixed but must be moved frequently. For instances discussions with design engineers have indicated the tremendous difficulties involved in attempting to insulate and heat the interior of a tank to meet the needs of operations in sub-arctic climates, without changing its silhouette and increasing very significantly its production costs. It appears that the possibility of controlling the temperature of the work space deserves much more careful consideration. Another possible approach to maintaining adequate temperature levels is suggested by the results of the present study and by previous research. For example, one study (6) of the efficiency of Signal Corps operators in extreme cold, conducted at the USAMRL, reported that "Part of the effect of cold on efficiency is related to the discomfort produced, even through mittens, by contact with the cold metal control handle." Instead of attempting to heat or case the entire work space it would appear well worthwhile to investigate more completely the feasibility of controlling temperatures of surfaces which the operator will be required to contact in performing his skills.

2. Selection of Control and Display Systems to Minimize Temperature Effects

The results of the present study, particularly when considered in the light of information available concerning differences in performance with various types of control and display systems, suggest that certain systems may have significant advantages over others for operations under extreme temperature conditions. For example, in addition to having other advantages (17), pressure control appears to be less affected than free movement control over a wider range of ambient temperatures. Further research on performance under extreme environmental conditions using various control and display systems may provide information of considerable value in selecting a system to meet particular operational requirements.

VI. SUMMARY AND CONCLUSIONS

There now has accumulated sufficient information to indicate that man's performance may be affected very significantly by the atmospheric conditions of the environment in which he operates. Variations in temperature both above and below an optimal range may impair his efficiency in "mental" as well as physical work. Certain components of a skill may be affected before others. The extent of the effects may be influenced by the level of the operator's skill, by the level of incentive under which he is performing and by his previous acclimatization to his work environment. These are matters of considerable practical importance in industry and, even to a greater extent, in the military services where man may be required to operate under the most extreme environmental conditions.

In order to insure that man can be prepared to perform as efficiently as possible and that the machines he must operate are designed to maximize his efficiency, it is necessary to examine by systematic research a wide variety of relations between environmental conditions and different types of performance. Although some information is already available, much further research needs to be carried out. The present study was designed to obtain information regarding the effects of ambient temperatures ranging from -10° to +40° C on five different measures of human performance: skill in using movement and pressure tracking controls, tactile and kinesthetic sensitivity, and strength of hand grip. The 2 types of tracking controls have wide military and industrial applications and the other 3 performances are basic to the operation of a great number of machine systems. Systematic records were also kept of the skin temperature of the fingers and forearm under control and experimental conditions.

The research design required the use of 12 groups of 6 subjects each. The groups were divided into 2 sets of 6, one set using movement and the other pressure controls throughout their tracking performance. All 12 groups were required to perform the various tasks in a series of "cycles" during which performances were measured in the following order: kinesthetic sensitivity, tactile sensitivity, hand grip and tracking. Two subjects from the same group were observed during a day's experimental session. The morning began with general instructions regarding the nature of the day's work, followed by 4 cycles of measurements. Exploratory studies had indicated that such preliminary training was sufficient to eliminate practice effects as significant variables during the experiment proper. The latter began in the early afternoon with one cycle of "control" measurements. This was followed by 4 cycles of "experimental" measurements made at one of 6 ambient temperatures. This was the only phase of the research in which the 6 groups of each set were given different treatments, otherwise they were all subjected to the same experimental conditions. One group in each set was exposed during this phase to each of the following ambient temperatures: +40°, +30°, +20°, +10°, 0°, and -10°. Immediately following the experimental series the subjects completed 2 further cycles under the same ambient temperature conditions as during the control measurements. This final phase of the research provided information on recovery from exposure to the experimental temperatures.

Seventy-two enlisted men in the United States Army served as subjects. They were assigned to particular groups required by the research design purely on the basis of what experimental conditions had been set up in the laboratory for the day on which they reported for work. Analysis of variance using measures recorded during the control series as indicative of pre-experimental levels of performance indicate that the groups did not differ in their initial performance and, therefore, inter-group comparisons are justified.

The techniques for controlling ambient temperature and humidity in the research rooms and for measuring the 5 different types of performance have been described in detail in the main body of this report and will not be repeated here. All except the techniques for measuring the tracking skills had been used by other research workers, but still their reliabilities under the present operating conditions were examined and found to be satisfactory. Skin temperatures were recorded using a Brown potentiometer and copper-constantan thermocouples.

The following results were obtained:

A. <u>Temperature Ranges of Effective Performance</u>

1. Certain performances, i.e., kinesthetic sensitivity, both average and constant errors, and pressure tracking, were significantly impaired at the low end of the temperature range but not at the high end. The other performances, i.e., tactile sensitivity, hand grip, and movement tracking, showed decrements at both ends, impairment being greater at the low than at the high.

2. Tactile sensitivity was most susceptible to variations in experimental temperatures, being impaired by changes on both sides of an optimal point at +30° C.

3. Measures of hand grip and movement tracking showed decrements as the experimental temperatures increased or decreased beyond the range +10° to +30° C.

4. Kinesthetic sensitivity and pressure tracking showed no effects of changes of experimental temperatures within the range +20° to +40° C, but were impaired as temperatures fell below +20° C.

B. <u>Relations between Performance and Duration of Exposure to Experimental Temperatures</u>

1. The relations between ambient temperature and effective performance just described were dependent upon the length of exposure to the experimental temperatures.

2. Movement and pressure tracking showed significant temperature effects during the first cycle of the experimental series, i.e., after an exposure of approximately 14 minutes.

3. Tactile sensitivity was affected significantly during the second cycle, i.e., after about 26 minutes exposure.

4. Strength of hand grip showed its first significant effects during the third cycle, approximately 46 minutes after exposure to the experimental temperatures began.

5. Neither measure of kinesthetic sensitivity was affected until the fourth cycle, i.e., after 58 minutes exposure.

C. Recovery from Exposure to Different Ambient Temperatures

1. Since recovery implies previous impairment it would be expected that the most pronounced evidence of recovery would be found at the 2 lowest experimental temperatures, which were shown to be associated with the greatest impairment in all the performances studied. The results supported this expectation.

2. There was evidence during the recovery period of improvement in the performance of the hand grip and movement tracking tasks for groups exposed to both high and low ambient temperatures. Both these performances had shown significant impairment at the extreme temperatures during the experimental series of measurements.

3. The length of the recovery period was insufficient for all performances except tactile sensitivity to regain their pre-experimental levels. Tactile sensitivity was affected after relatively short exposures to the experimental temperatures and the evidence indicates that it also recovered very rapidly.

D. Relations between Skin Temperature and Ambient Temperature

1. In general skin temperature of the fingers changed during exposure to the experimental temperatures, the only exception being Group 2, at +30° C. The most striking changes were at -10° and 0° C, where there was rapid initial cooling of the skin, tending to level off at 8° and 14° C, respectively, as length of exposure increased. At +40° C the trend was in the opposite direction, skin temperature rising by approximately 3 degrees at its maximum. During the recovery series skin temperature returned toward 33° to 34° C, its level during the

control series. At the 2 coldest temperatures the rate of recovery was rapid at first, tending to decrease as duration of exposure to the temperature of the recovery room increased. Tau correlations between ambient temperatures and the final skin temperature readings for the preferred and non-preferred hands were 0.96 and 0.92, respectively. Such high correlations indicate that relations between the various performances and skin temperature were similar to those between the performances and ambient temperature as previously reported.

2. Despite the fact that the forearm was covered by protective clothing thermocouples attached to its ventral and dorsal surfaces recorded significant changes during the experimental series in all temperature groups except those exposed to decreasing ambient temperatures. Tau correlations between ambient temperature and the final skin temperature readings of the experimental series were 0.83 and 0.87 for the dorsal and ventral surfaces, respectively. One feature of the forearm temperatures which deserves special note was the tendency at +10°, 0°, and -10° for the magnitude of the differences between skin temperatures of the 2 surfaces to increase consistently as length of exposure to the experimental temperatures increased.

E. Effects of Contact with Metal Control Surfaces on Skin Temperature

1. Examination of the data shows that at the 2 lowest experimental temperatures contact between the fingers of the preferred hand and the brass control surface during performance of the tracking task had a systematic effect on skin temperature. In all instances skin temperatures of the preferred hand immediately after release of the control surface were lower than temperatures of the non-preferred hand which had been supported free of contacts with any surfaces. This lowering of skin temperature was always followed by a marked re-warming of the preferred hand and then a cooling until re-warming took place.

2. This systematic cycle of events did not occur at temperatures of +10° C and above, where the skin temperature of the preferred hand was fairly consistently higher than that of the non-preferred.

These results are of interest in 2 general regards. First, they add to our knowledge concerning the effects of variations in ambient temperature on human performance. They support the general trends of previous research in indicating that signs of impairment in performance may appear when temperature varies outside rather narrow limits and that certain characteristics of this impairment differ in different types of human performance. They show that different sense modalities are differentially sensitive to temperature variations in terms of the durations of exposure necessary to produce signs of impairment and in terms of the characteristics of their recovery following exposure.

Secondly, the results of the present research have provided information which can be of value in the design of machines and equipment to maximize the efficiency with which man-machine systems can function under adverse atmospheric conditions. Frequently impairment in man's performance constitutes the main limitation of such systems. If steps are to be taken to minimize this impairment certain basic information about its nature and characteristics is essential. The present research has provided such information about certain types of human performance. It has suggested ways in which different approaches to maintaining adequate levels of temperature, e.g., protective clothing, heating the work space, locally heating control surfaces may be tested. It also has indicated that some control and display systems may be used more efficiently than others under extreme temperature conditions.

The present research could be concerned with only a few of the many types of human performance required in military operations. It has suggested the need for further systematic investigations of a similar nature. Such investigations should be designed to determine relations between environmental conditions and performance, including ranges over which efficient performance can be expected; to study the effects of duration of exposure on performance; and to observe the characteristics of recovery from exposure. The environmental variables investigated should include humidity, air velocity and radiation as well as ambient temperature, and particular attention should be given to the effects of interactions between these variables. The performances studied should be representative of the wide variety of skills required of military personnel and emphasis should be placed on the effects of the environmental variables on perceptual as well as motor aspects of performance. Different methods for overcoming the adverse effects of these environmental variables should be put to experimental test.

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